Higgs Physics : The origin of mass

or

The Quest for Electroweak Symmetry Breaking

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April 21, 2004

Outline

- The Standard Model (SM)
- Dynamics of Electroweak Symmetry Breaking
- Precision Measurements and the SM Higgs Boson
- Where does the Standard Model Breaks down?
- The hierarchy Problem of the SM Higgs Sector
- Supersymmetry
- The race for the Higgs Boson
- Conclusions

The Forces of Nature

- Why are the four forces in nature so different?
- How do we try to model them?

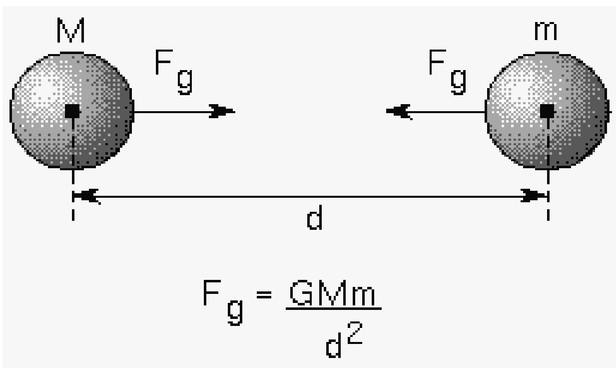
The Fundamental Particles

- quarks and leptons (matter), and gauge bosons (force carriers)
- How do they get mass?
- How do we test the mechanism for the origin of mass ?

Gravitational and electromagnetic interactions

- Gravity

Attractive force between 2 massive objects:



prop. to product of masses

$$G = 1/M_{Pl}^2$$

Is very weak unless one of the masses is huge, like the earth

- Electromagnetism

Attracts particles of opposite charge

forces within atoms and

between atoms (residual em.i.)

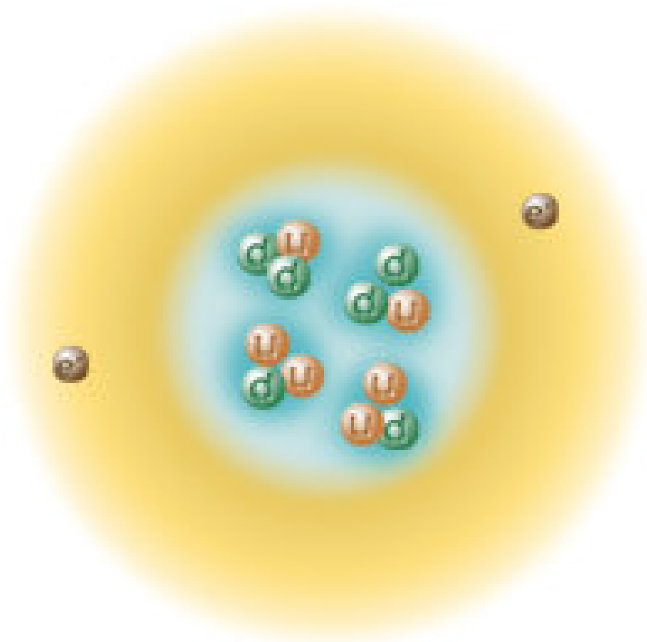
Electrons interact with protons

Via quantum of e.m. energy

⇨ the photons $s_\lambda = 1$ $m_\gamma = 0$

Modeled by a theory based on U(1) gauge symmetry

Strong Interactions



Atoms are made from
protons, neutrons and electrons

D.I.S. of electrons with protons or neutrons at high energies shows that protons and neutrons are not fundamental

p → u u d
n → u d d

formed by three quarks, bound together by the gluons of the strong interactions

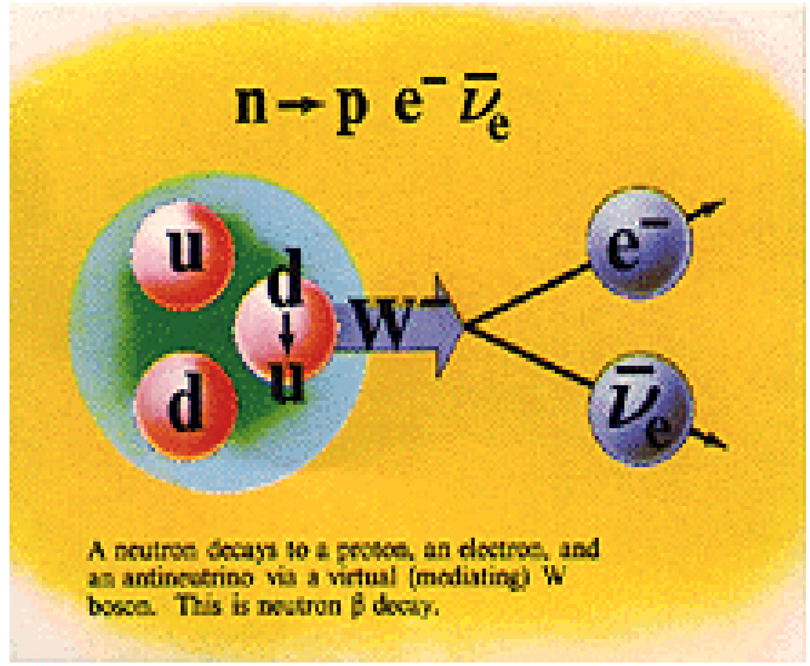
Modeled by a theory based on $SU(3)_C$ gauge symmetry

Very strong at large distances ⟹ confinement $\equiv$ no free color particles

Weak Interactions

Observation of Beta decay

demanded a
novel interaction



Short range forces only existent inside the protons and neutrons, with massive carriers:

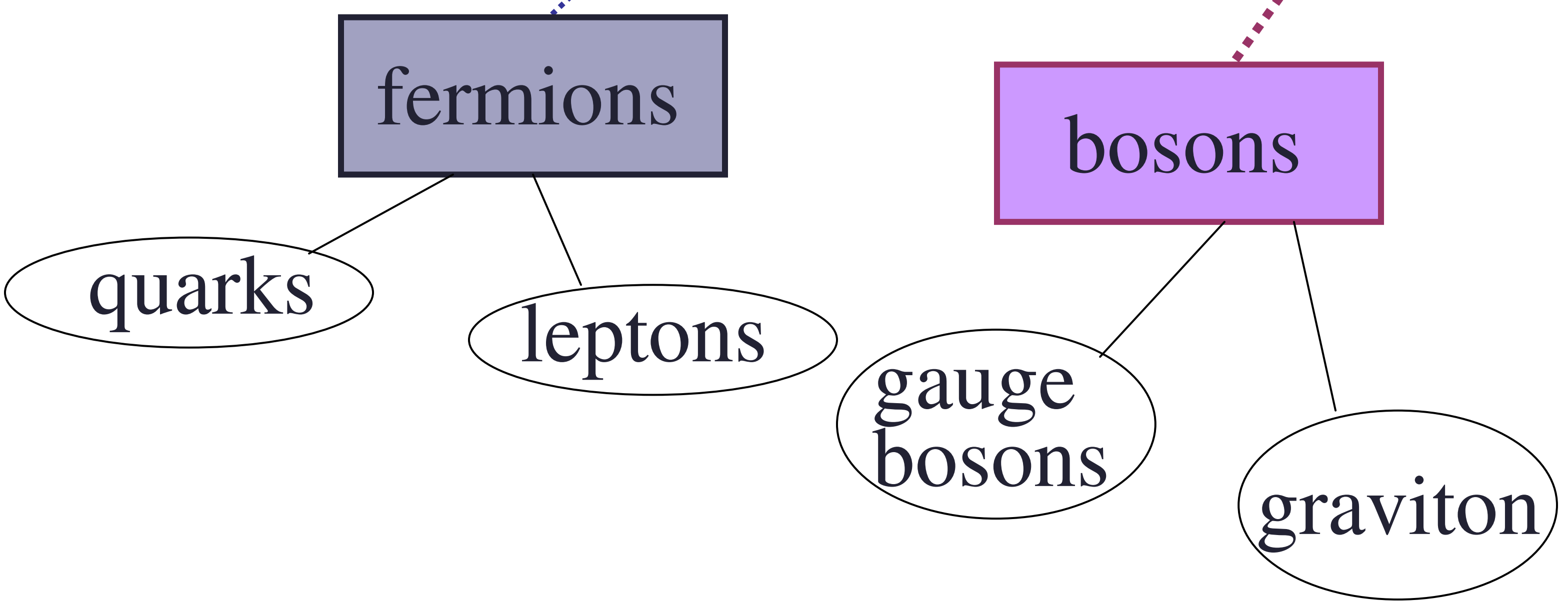
gauge bosons: W and Z

Modeled by $SU(2)_L$ gauge symmetry

assigns 2 isospin charges $\pm 1/2 \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu_L \\ e \end{pmatrix}_L$

The Complete Picture

The universe is made out of matter particles and held together by force particles



The Standard Model

A quantum theory that successfully describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

based on a gauge field theory with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

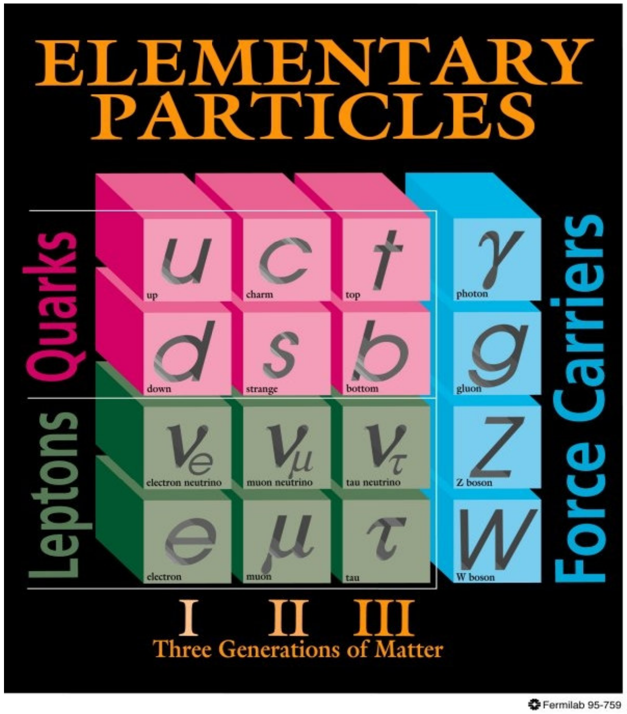
12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings: g_1, g_2, g_3

The matter fields :

3 families of quarks and leptons with the same quantum numbers under the gauge groups



Matter: 3 families of quarks and leptons have the same properties (quantum numbers) under the symmetries of nature

BUT they have very different masses !

$$m_e \approx 0.5 \;\; 10^{-3} GeV \qquad \frac{m_\mu}{m_e} \approx 200 \qquad \frac{m_\tau}{m_\mu} \approx 20$$

Largest Hierarchies: $m_t \approx 175 GeV$ $\qquad \frac{m_t}{m_e} > 10^5$

neutrino masses as small as $10^{-10}\,\mathrm{GeV}$

Crucial Problem:

Due to the chiral nature of the model, fermion mass term $L = m\,\overline{\psi_L}\psi_R + h.c.$ is not invariant under gauge group

Also, how to give mass to $\mathrm{SU}(2)_L$ gauge bosons?

$$m_W = 80.449 \pm 0.034\, GeV \qquad m_z = 91.1875 \pm 0.0017\, GeV$$

The quest for electroweak symmetry breaking

is the search for the dynamics that generates the Goldstone bosons that are the source of mass for the W and Z.

Possible Choices for EWSB dynamics:

- **Weakly-interacting self coupled elementary (Higgs) scalar dynamics**
- **Strong-interaction dynamics among new fermions (mediated perhaps by gauge forces)**

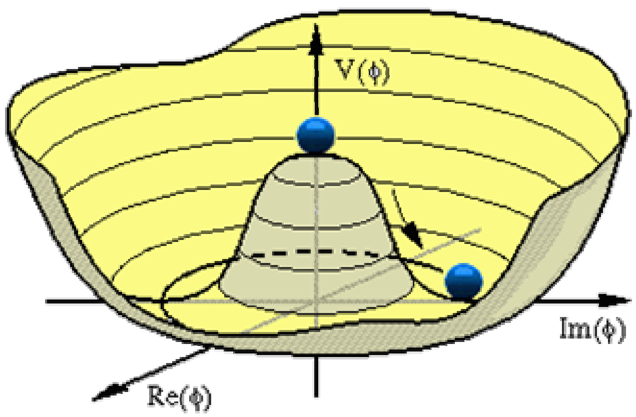
Both mechanisms generate new phenomena with significant experimental consequences

The dynamics of electroweak symmetry breaking must be exposed at or below the 1 TeV energy scale

EWSB Dynamics of the Standard Model

- Introduce a complex doublet self-interacting scalar field ⟹ Higgs with non-trivial quantum numbers under $SU(2)_L \times U(1)_Y$

The Higgs Mechanism



The Higgs field prefers to acquire a nonzero value to minimize its energy

$$V(\phi) = -m^2\phi^2 + \frac{\lambda}{2}\phi^4$$

Spontaneous breakdown of the symmetry, generating 3 Goldstone bosons (massless) which are absorbed by the W and Z,

one scalar degree of freedom left over

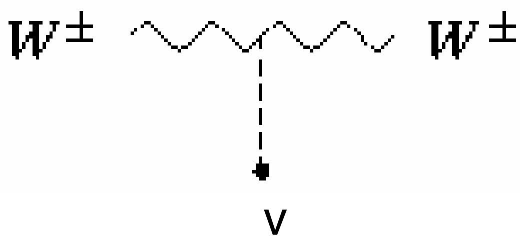
In quantum field theory

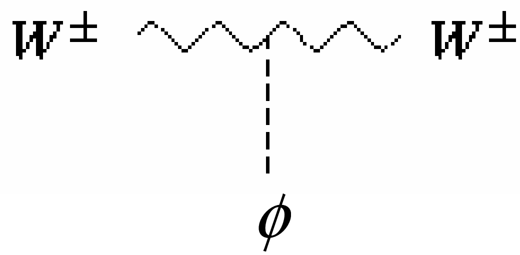
fields are associated with particles

Higgs Fields → Higgs Boson particle

Mass Generation and Higgs Couplings

- Gauge bosons acquire mass via interaction with the Higgs vacuum condensate v





hence: $g_{\phi W^+W^-} = 2m_W^2 / \mathrm{v}$ also $g_{\phi ZZ} = 2m_Z^2 / \mathrm{v}$

Higgs couplings to bosons are prop. to corresponding boson squared-mass

Higgs neutral under strong and electromagnetic interactions $\Longrightarrow$ no coupling

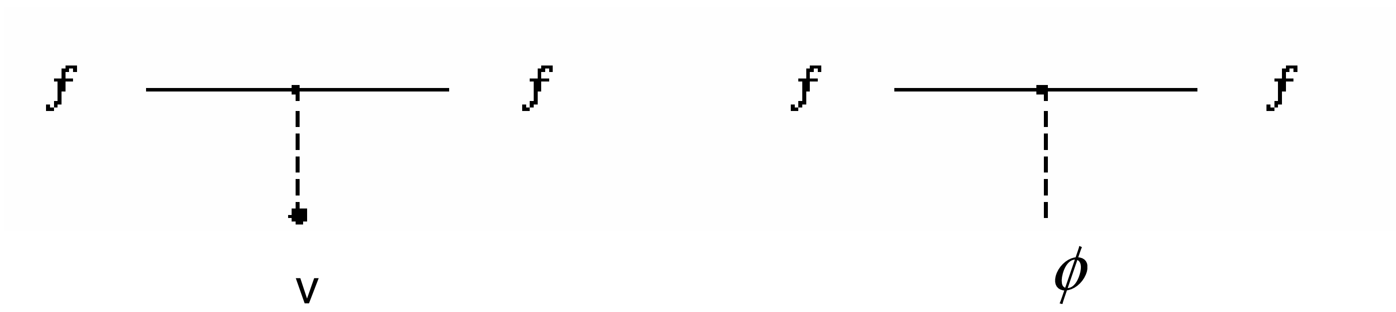
$m_\gamma = 0 \quad m_g = 0$

Massles Gauge Bosons

Exact Symmetry

$$SU(3)_c \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_c \times U(1)_{em}$$

- The quarks and charged leptons acquire mass via Yukawa interactions once the Higgs acquire v.e.v.



Higgs Coupling to fermions prop. to corresponding fermion mass

$$g_{\phi f \bar{f}} = m_f / \mathrm{v}$$

Higgs mass proportional to Higgs self coupling λ

unknown parameter of the model

$$m_\phi^2 = 2\lambda \mathrm{v}^2$$

All fundamental particles but one have been seen at accelerators

The missing particle of the Standard Model

The Higgs Boson

Is quite essential

finding the Higgs boson is the key to discover if the Higgs field exist, and hence to prove if our simplest explanation for the origin of mass is indeed correct.

Precision Tests of the Standard Model

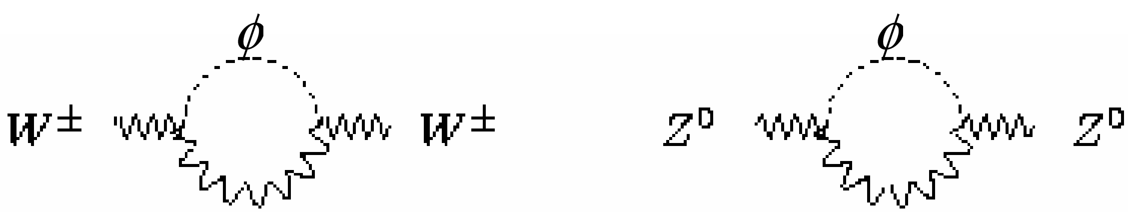
- The Standard Model has been tested with very high precision (one part in a thousand!)

at experiments around the world

CERN, Fermilab, SLAC

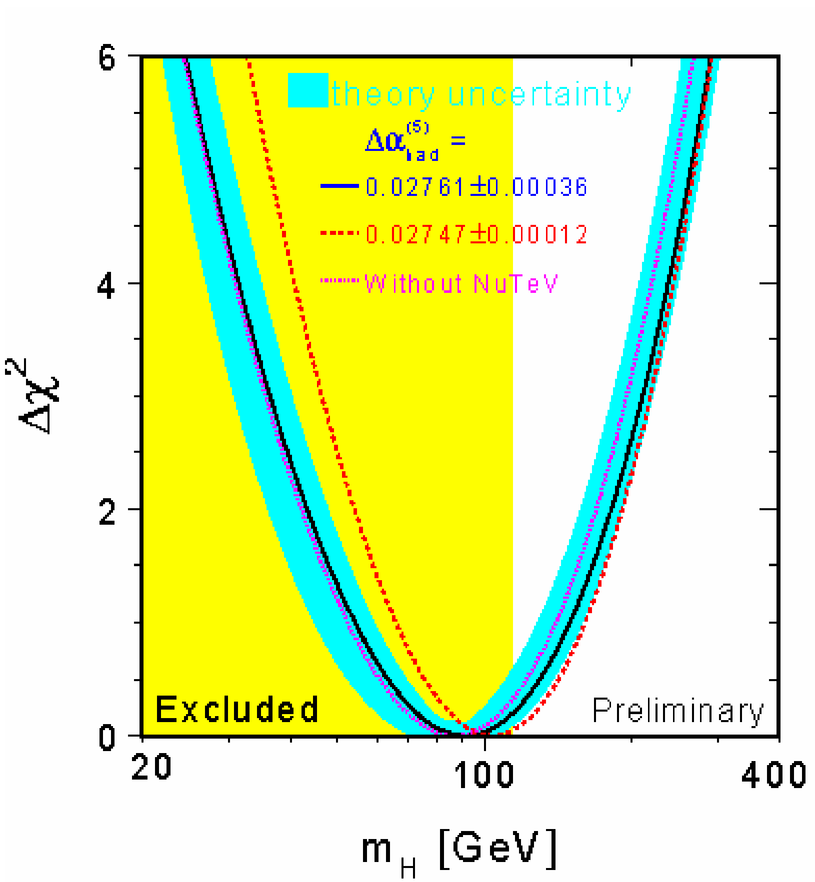
The pillar of particle physics: explains data collected in the past several years and describes physical processes up to energies of about 100 GeV

Although the Higgs boson has not been seen and its mass is unknown, it enters via loop corrections in electroweak observables: particle masses, decay rates, etc



All electroweak parameters have at most logarithmic dependence on m_ϕ
However, preferred value of m_ϕ can be determined

Constraints on m_ϕ from precision electroweak data



$$m_\phi = 78^{+48}_{-31}\,\mathrm{GeV}$$

$m_\phi < 193\ \mathrm{GeV}$ at 95% C.L.

Within the SM, the Higgs is expected to be lighter than about 200 GeV

- **If New Physics beyond the SM exists, most certainly will couple to SM particles giving contributions to SM observables via quantum correc.**

- It has been shown that to avoid a light Higgs boson, the New Physics beyond the SM must be accompanied by new phenomena at scales below 1 TeV

It can be detected at present and future colliders:

1. through direct detection
2. by improved meas. which detect deviations from SM

The Standard Model: an effective theory

1. The SM is not valid at energies above $M_{Pl} \approx 10^{19} GeV$ where gravity can no longer be ignored

2. SM neutrinos are massless, but neutrino masses have recently been observed to be very small $m_\upsilon / m_e \leq 10^{-7}$

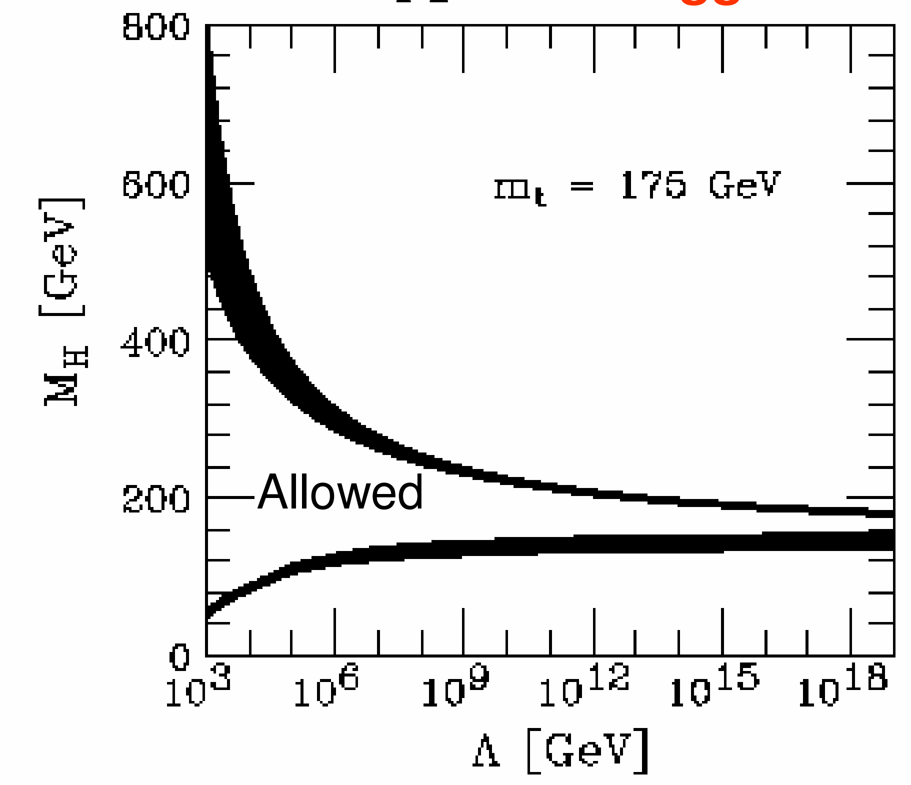
   Theories with fundamental scales of order $M >> \mathrm{v}$ generate neutrino masses $\mathrm{v}^2 / M \longrightarrow M \approx 10^{15} GeV$

3. Radiative corrections can destabilize the Higgs potential or render the Higgs self coupling to infinity
4. Has some inelegant mathematical issues: The hierarchy problem
5. It does not allow for unification of all forces in nature
6. It does not explain: Dark Matter
   The Matter-Antimatter asymmetry
   The fermion mass hierarchies

Perturbativity and Stability Bounds

- **Higgs potential unstable at large values of the Higgs field** $\phi > \Lambda$ **if the Higgs mass is too small** ⇨ **light Higgs** $m_\phi \leq 130\,\mathrm{GeV}$ **prefers new physics at** $\Lambda \approx 10^4 - 10^{11}\,GeV$

- **The value of the Higgs self-coupling runs off to infinity at an energy scale above** Λ **if the Higgs mass is too large.**



If SM description valid up to scales

$$\Lambda \approx 10^{13} - 10^{19}\,GeV$$

then 130 GeV $\leq m_\phi \leq$ **200 GeV**

The Hierarchy Problem of the SM Higgs Sector

- SM is an effective theory $\Longrightarrow$ low energy quantities (masses, couplings) expected to be given as a function of parameters of the fundamental theory valid at Q> $\Lambda_{eff.}$

✦ **low energy dimensionless couplings: receive quantum corrections prop. to log ($\Lambda_{eff.}$)**

✦ **what about the Higgs potential mass parameter m ?** $v^2 = m^2 / \lambda$

Quantum corrections to m^2 are quadratically divergent

$$m^2 = m^2(\Lambda_{eff.}) + \Delta m^2$$

$$\Delta m^2 \approx \frac{n_W g^2_{hWW} + n_h \lambda^2 + n_f g^2_{hf\bar{f}}}{16\pi^2} \Lambda^2_{eff.}$$

to explain v $\approx O(m_W)$

either $\Lambda_{eff.} \leq$ **1 TeV**

or extreme fine tunning to give cancellation

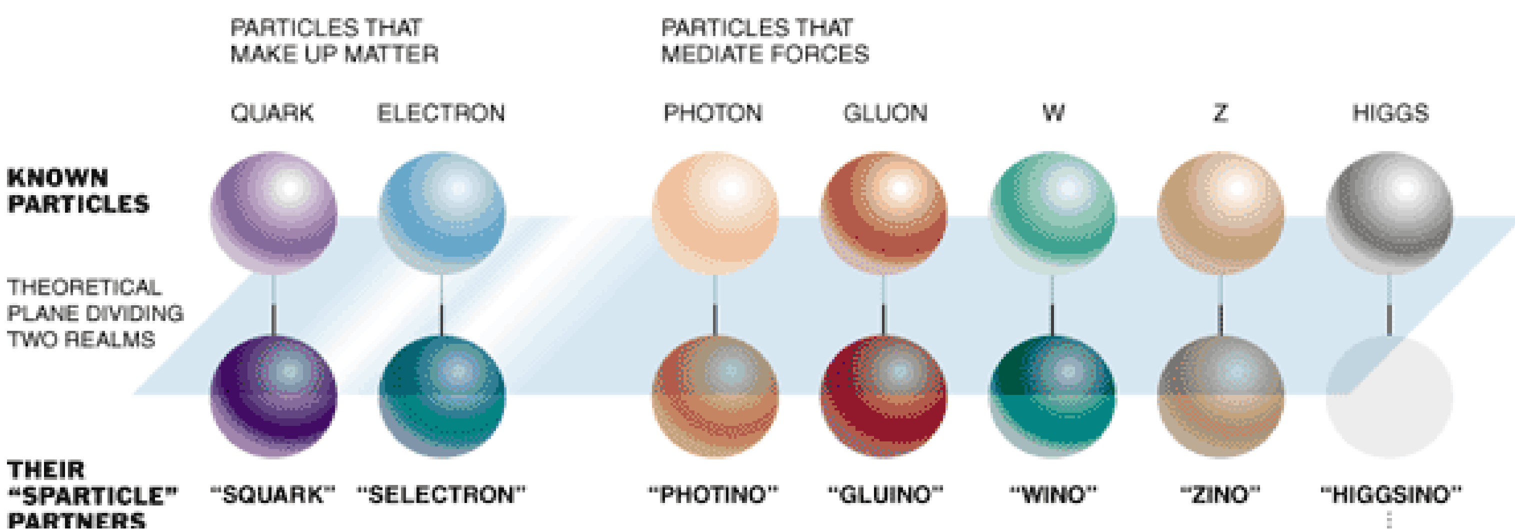
Low energy Supersymmetry

<u>lesson from history</u>: electron self energy → fluctuations of em fields generate a quadratic divergence but existence of electron antiparticle cancells it, otherwise QED will break down well below M_{Pl}

Will history repeat itself? Take SM and double particle spectrum

New Symmetry → SUPERSYMMETRY (SUSY)

fermions ⟷ **bosons**

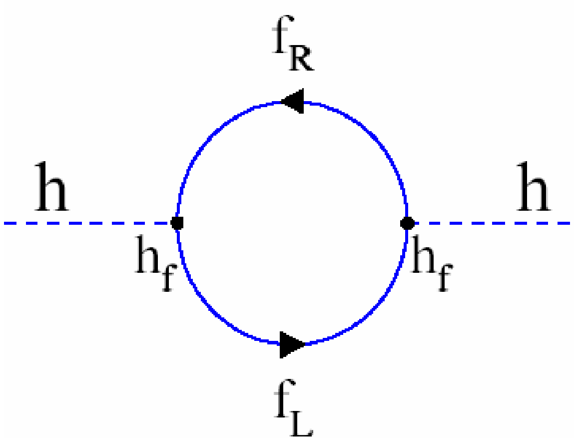


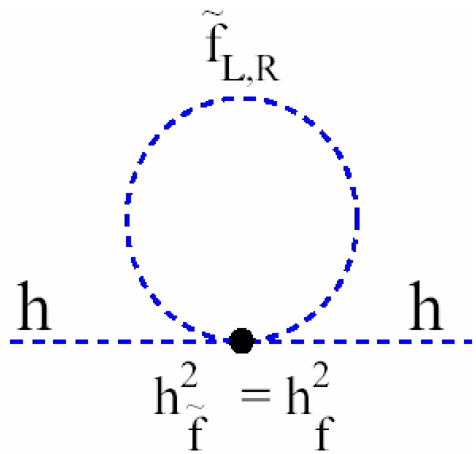
For every fermion there is a boson of equal mass and couplings

Self energy of an elementary scalar related by SUSY to the self energy of a fermion ⇨ only log dependence on fundamental high energy scale!

Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

$$\Delta m^2 \approx g^2_{hf\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff}/m_h^2)$$





SUSY must be broken in nature: no SUSY partner, degenerate in mass with its SM particle has been seen

In low energy SUSY: quadratic sensitivity to $\Lambda_{eff.}$ replaced by quadratic sensitivity to SUSY breaking scale

The scale of SUSY breakdown must be of order 1 TeV, if SUSY is associated with scale of electroweak symmetry breakdown

⋆ **If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV range or below**

1. solve the hierarchy problem
2. generate EWSB by quantum corrections
3. Allow for gauge coupling unification at a scale $\approx 10^{16}\,\mathrm{GeV}$
4. induce a large top quark mass from Yukawa coupling evolution.
5. provide a good dark matter candidate: the lightest neutralino
6. provide a possible solution to baryogenesis

⋆ **SUSY particle masses depend on specific mechanism of SUSY breakdown** $\longrightarrow$ still not understood

TeV SUSY regime can give a glimpse of Planck scale physics

⋆ **<u>Minimal model</u>: 2 Higgs SU(2) doublets necessary to generate mass to up and down quarks and leptons and preserve gauge symmetry after quantum corrections**

Higgs Physics: important tool in understanding Supersymmetry

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TeV SUSY regime can give a glimpse of Planck scale physics

The Higgs Sector in the Minimal SUSY Standard Model

- **2 complex doublets have eight degrees of freedom.**
  → 3 Goldstone bosons absorbed by the W and Z

- **2 neutral scalar comp. acquire vacum expectation values:** $\mathrm{v}_1, \mathrm{v}_2$

- **The gauge boson masses fix** → $\mathrm{v}^2 = \mathrm{v}_1^2 + \mathrm{v}_2^2 = 246 GeV$

- **5 physical states remain:**

2 CP-even h, H **with mixing angle** α
1 CP-odd A **and a charged pair** $H^{\pm}$

All Higgs masses and couplings given in terms of 2 parameters

m_A **and** $\tan\beta = \mathrm{v}_2 / \mathrm{v}_1$

If $m_A >> m_Z \Rightarrow$ **decoupling limit**

lightest Higgs SM-like couplings with $m_h \leq m_Z$

other Higgs bosons heavy and roughly degenerate

Supersymmetric relations between couplings imply that $m_h \leq m_Z$

After quantum corrections, Higgs mass shifted due to incomplete cancellation of particles and superparticles in the loops

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right],$$

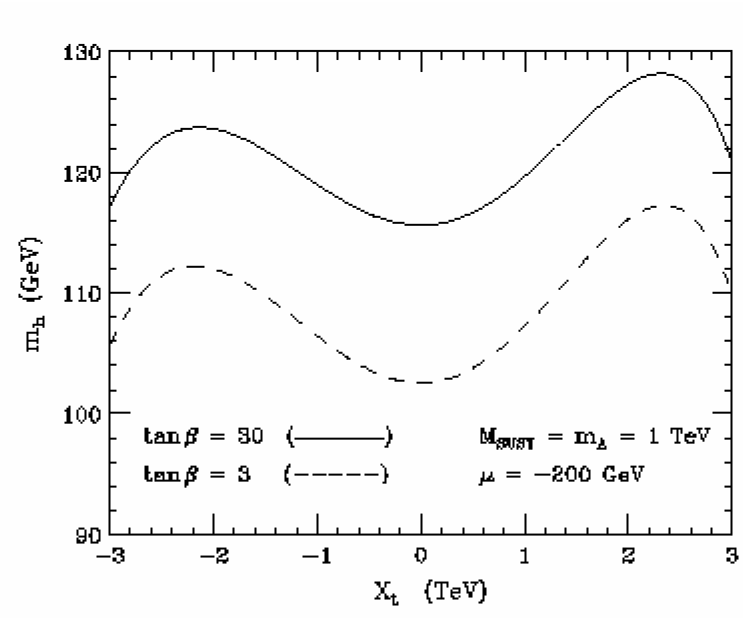
where $X_t \equiv A_t - \mu \cot\beta$ **governs the stop mixing and**

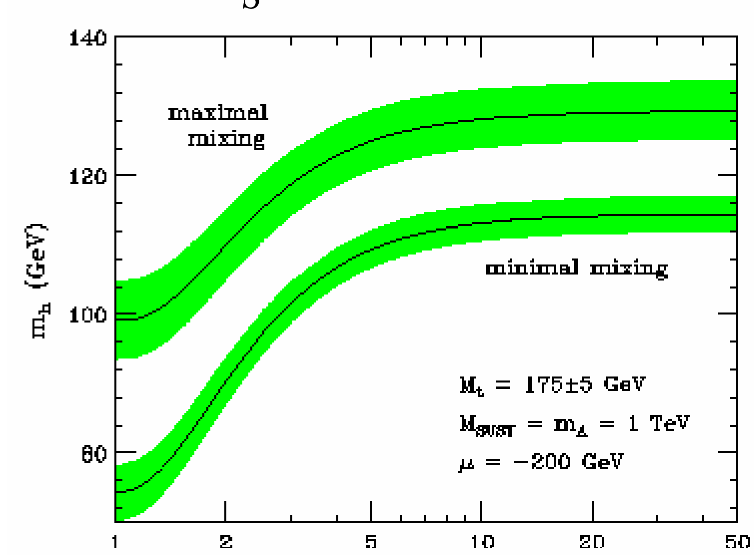
M_S^2 **is the average stop-squark squared- mass**

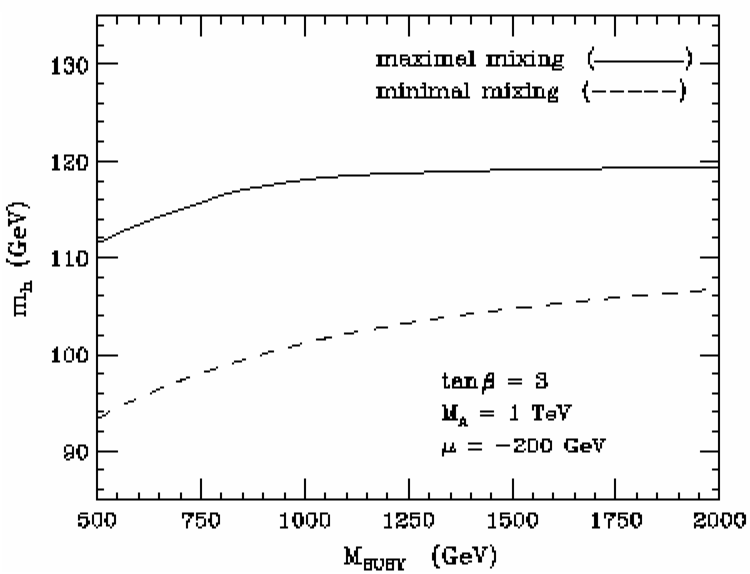
- **<u>Main Quantum effects</u>:** m_t^4 **enhancement ; dependence on the stop mixing** X_t **; logarithmic sensitivity to the stop mass**

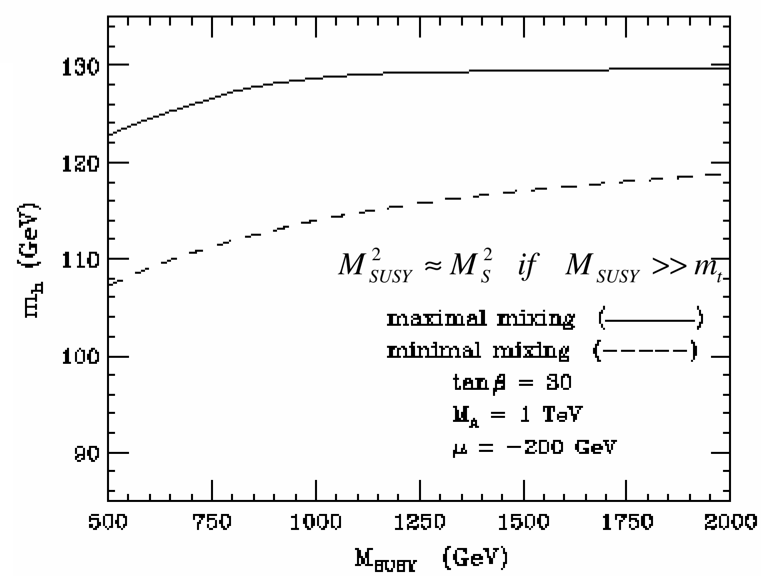
Upper bound $m_h \leq 135 GeV$ → stringent test of the MSSM

assuming M_S no heavier than 2 TeV









The Search for the Higgs Boson

If the Higgs Boson is created , it will decay rapidely into other particles

- **The past: The Large Electron Positron Collider - LEP**

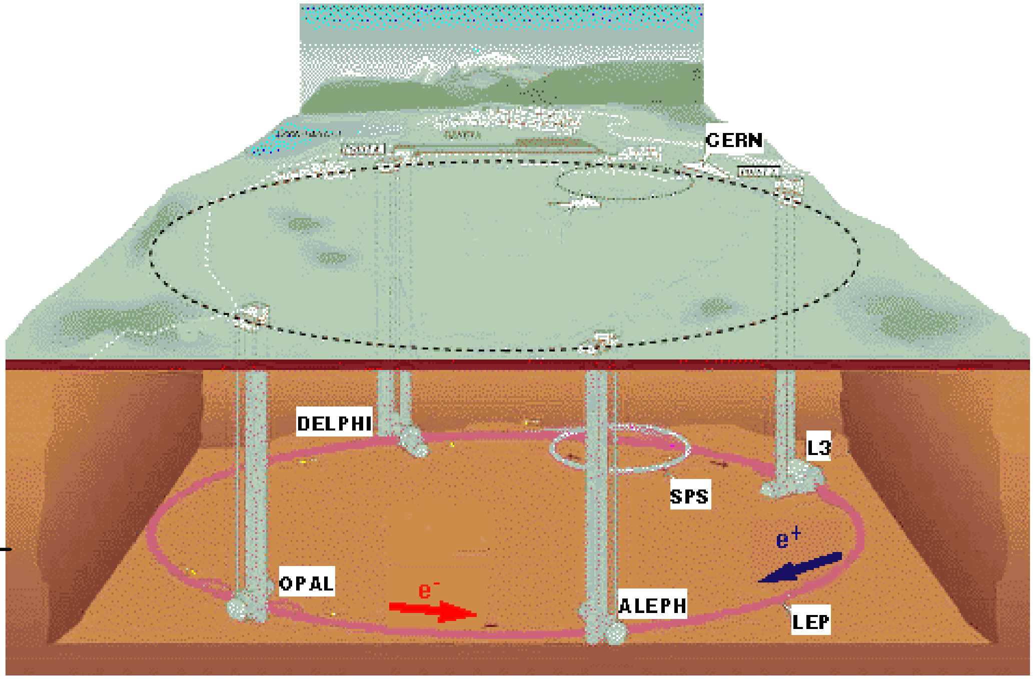
At LEP energies mainly

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z$$

with $H_{SM} \rightarrow b\bar{b}, \tau^+\tau^-$

and

$$Z \rightarrow q\bar{q}, l^+l^-, \nu\bar{\nu}$$



In case of SUSY Higgs one can also search for $e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$

Radiative corrections can have important impact on Higgs Branching ratios

Example: main decay mode $h \rightarrow b\bar{b}$ strongly suppressed in some MSSM regions

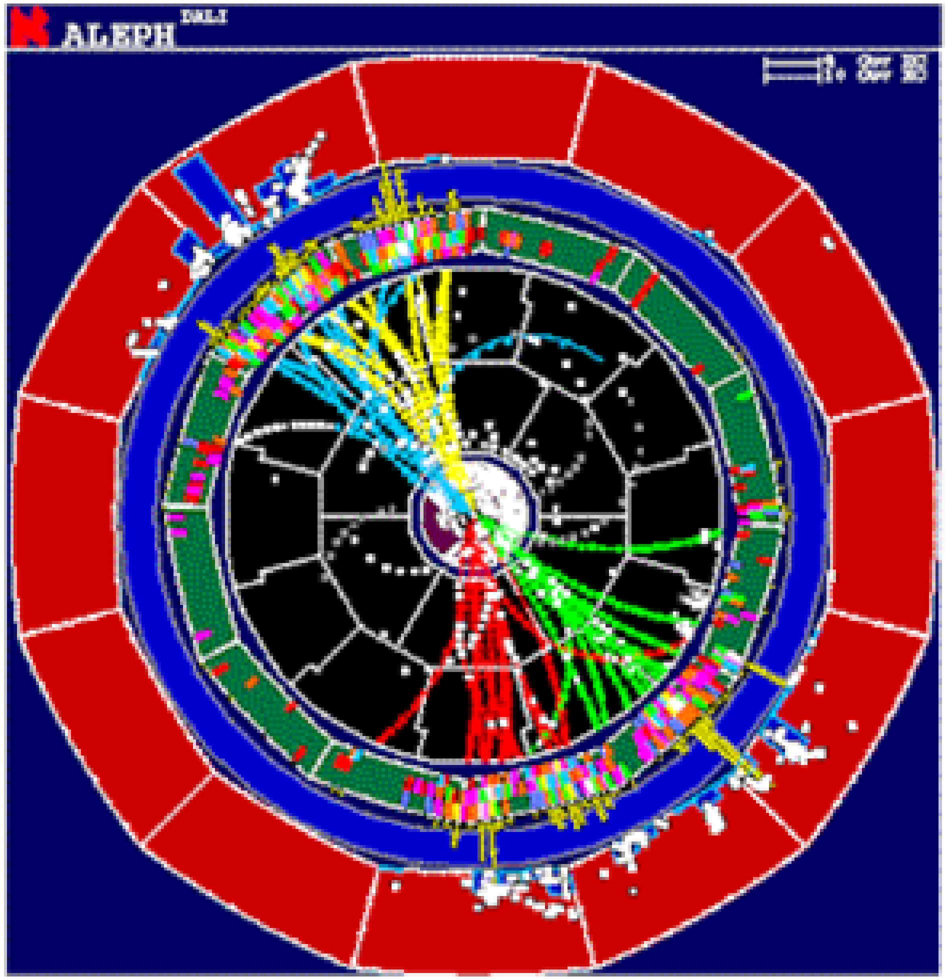
Higgs Particle Search at LEP (Aleph detector)

Higgs candidate with mass of about 114 +- 3 GeV and three identified b quarks

SM Higgs Boson 95% C.L. limit

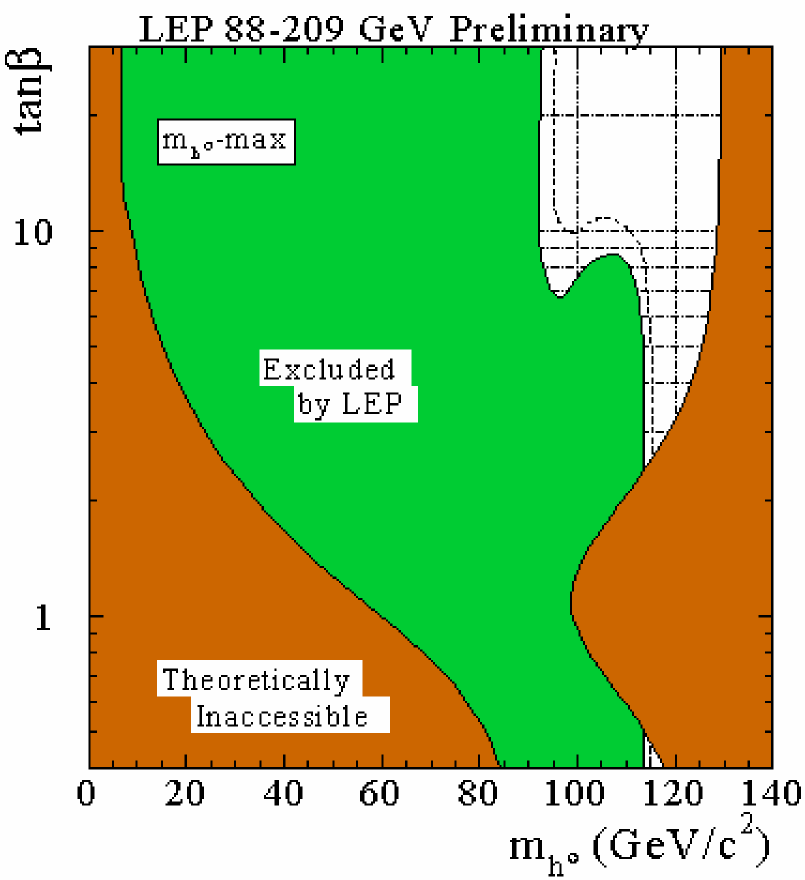
$$m_{H_{SM}} > 114.6 \, GeV$$

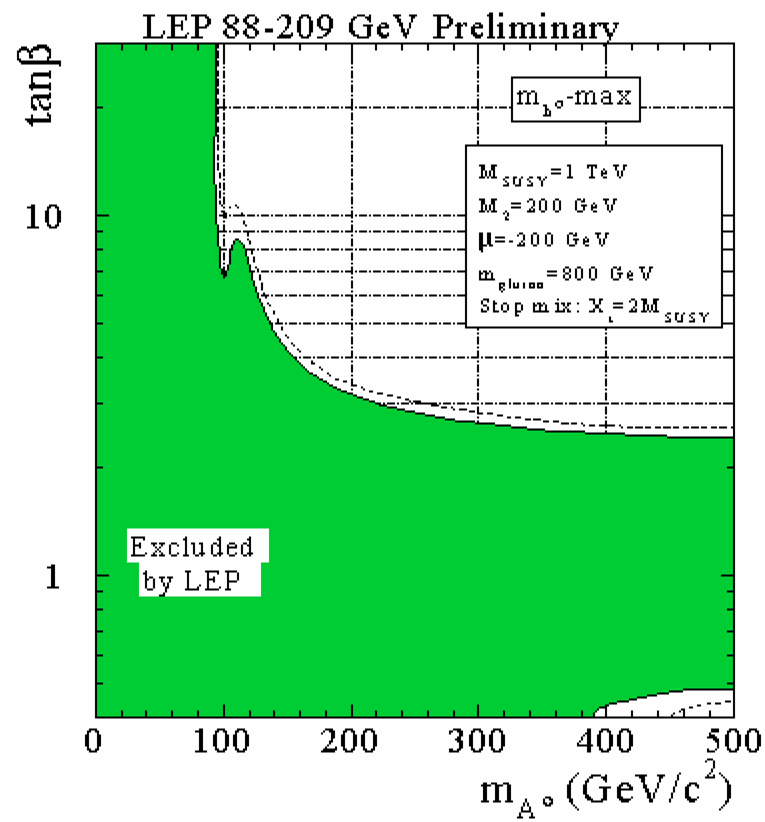
But, tantalizing hint of a Higgs with mass about 115 – 116 GeV (just at the edge of LEP reach)



Present Status of MSSM Higgs searches

95%C.L. limits



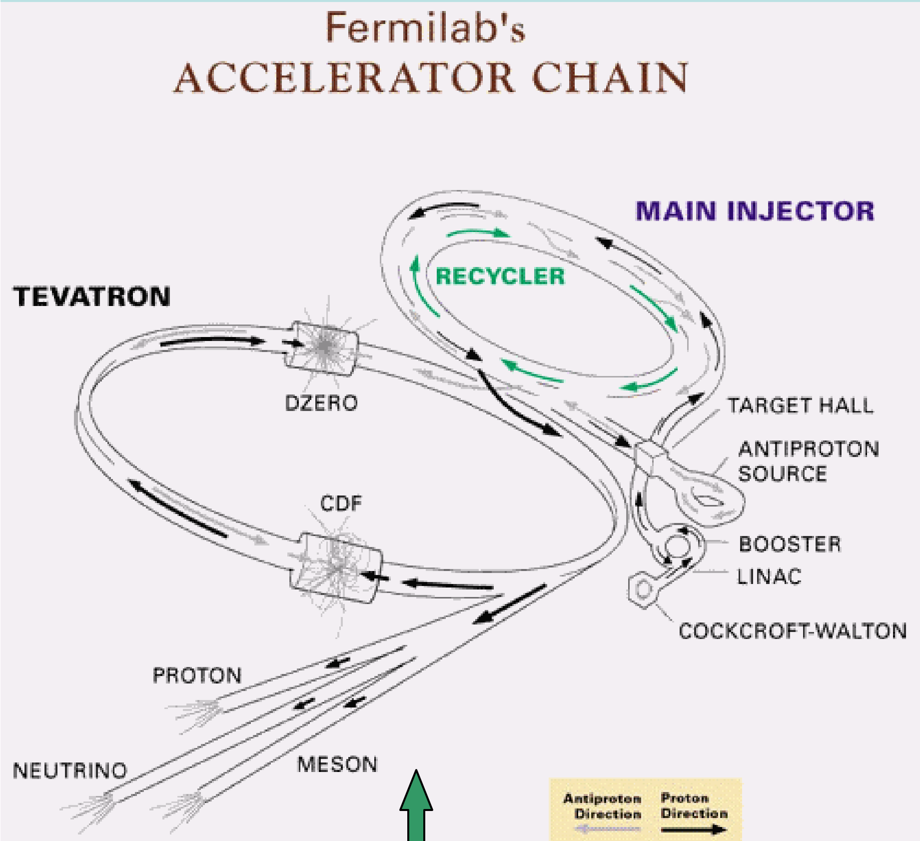


MSSM Higgs $m_h > 91.0 GeV; m_A > 91.9 GeV$

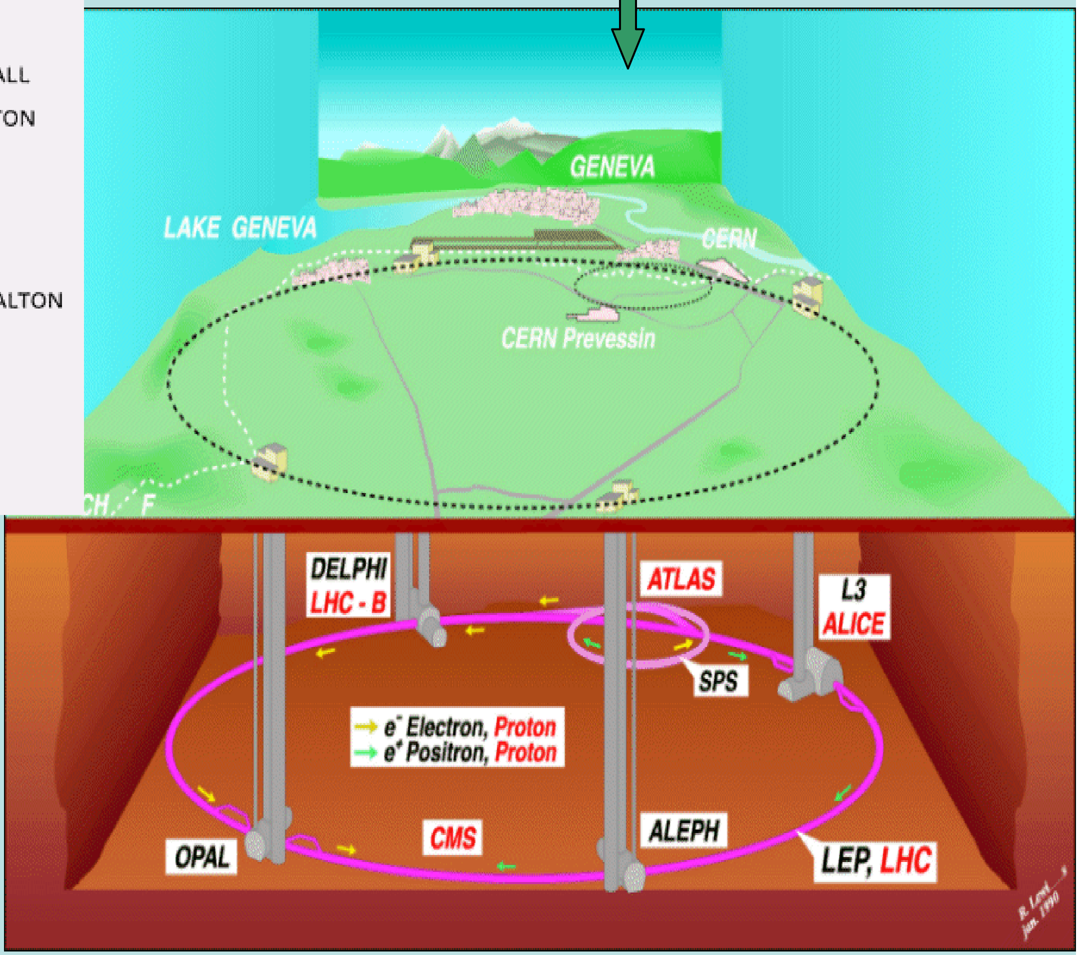
Charged Higgs $m_{H^\pm} > 78.6 GeV$

SM-like Higgs $m_h > 114.6 GeV$

The Race for the Higgs Bosons



Large Hadron Collider (LHC) at CERN



The Tevatron at Fermilab

The Race for the Higgs Boson

Future Colliders

collider	beams	[TeV] CM energy	[fb^{-1}/yr.] luminosity	start date
Tevatron	$\bar{p}p$	2	0.1 – 2	2001
LHC	pp	14	10—100	2007
LC [TESLA]	e^+e^-	0.5—1	50—500	???

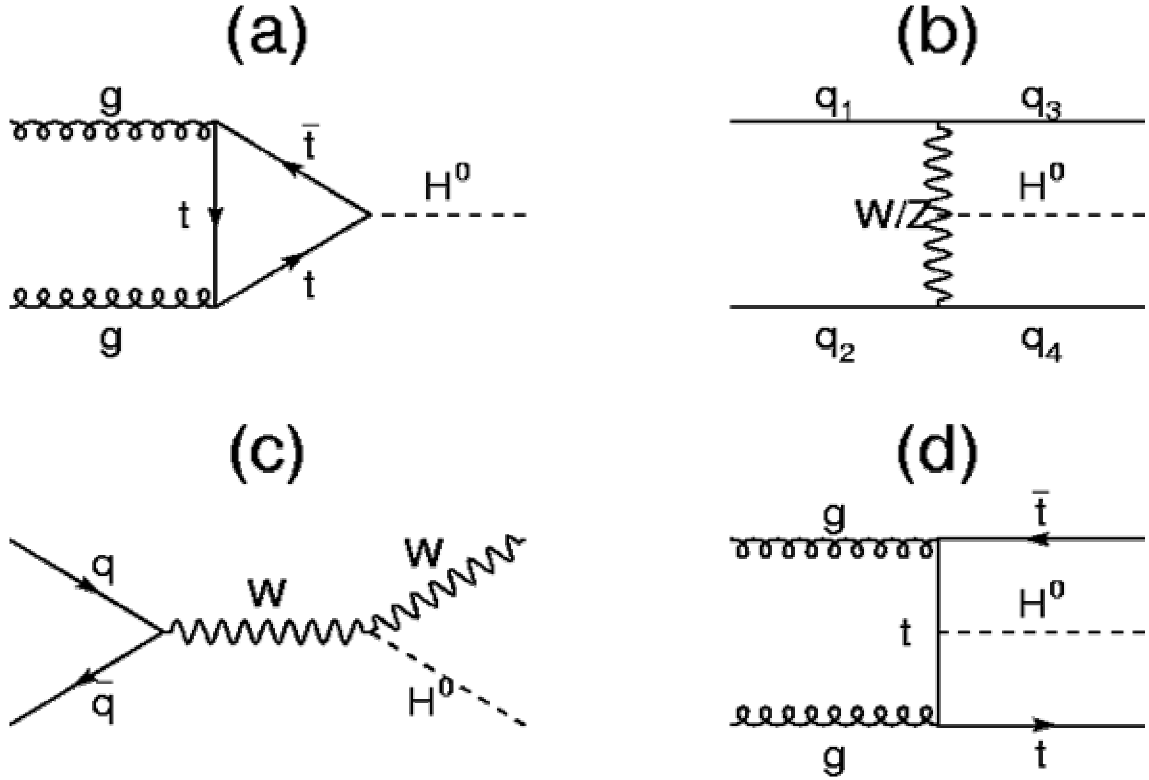
Next chance to reveal mechanism that can explain the origin of mass in nature → at Fermilab!

The first step is discovery: Observe one Higgs boson or more.

Next Step: measure its basic properties : mass, spin, width, CP quantum numbers; couplings to boson and fermions, Higgs self couplings and reconstruct Higgs potential, Higgs branching ratios

Use precision measurement of basic properties to learn about basic model of nature: Is this scalar a Higgs boson? Disentagle between SM , the MSSM, other non-minimal Higgs sector? Investigate CP viol., beyond the SM , via effects in the Higgs sector; Higgs mixings in ED

SM Higgs production processes at hadron colliders



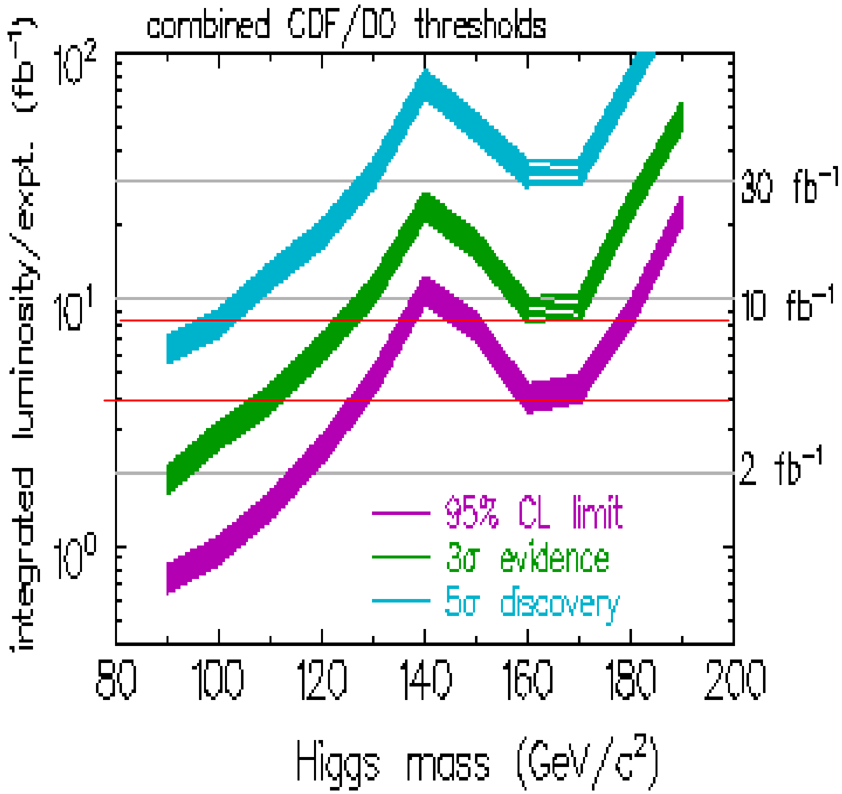
$$gg \to H_{SM} \to \gamma\gamma, \quad gg \to H_{SM} \to VV^{(*)} \quad with \quad V = W, Z$$

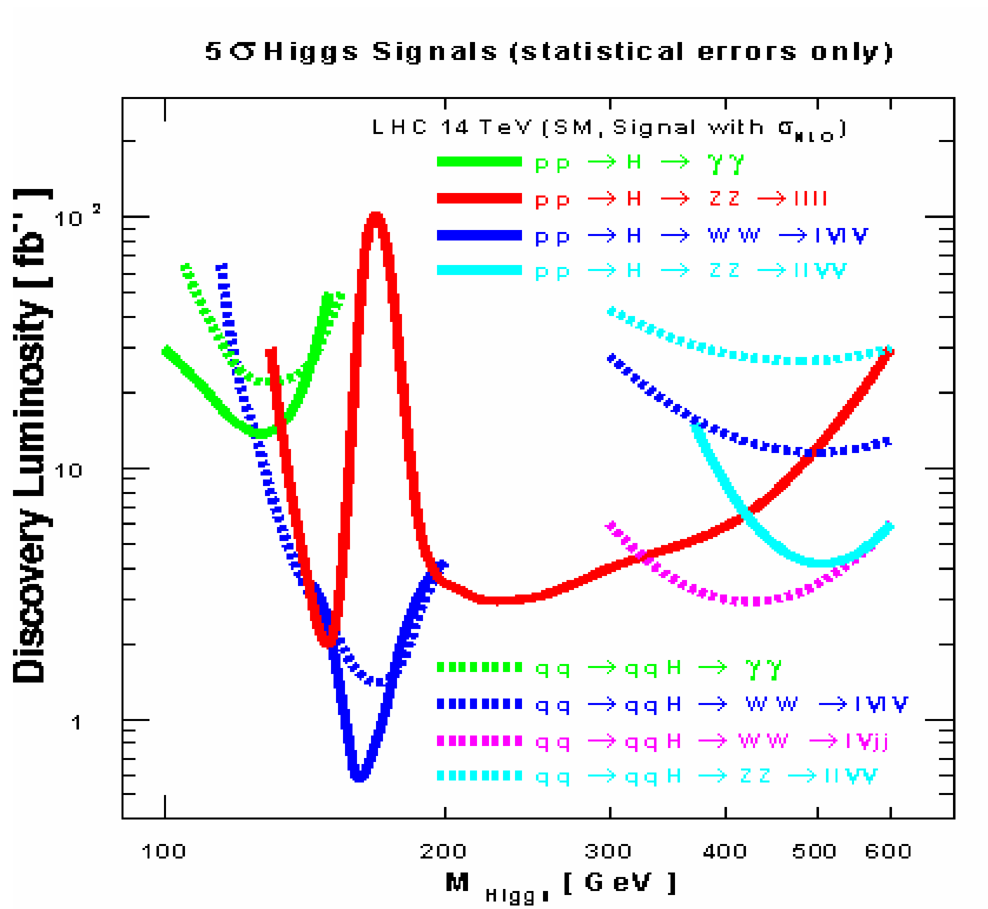
$$qq \to V^{(*)}V^{(*)} \to qqH_{SM}, \quad H_{SM} \to \gamma\gamma, \tau^{+}\tau^{-}, V\ V^{(*)}$$

$$q\bar{q}^{(')} \to V^{(*)} \to VH_{SM}, \quad H_{SM} \to b\bar{b}, WW^{(*)}$$

$$gg, q\bar{q} \to t\bar{t}H_{SM}, \quad H_{SM} \to b\bar{b}, \gamma\gamma, WW^{(*)}$$

SM Higgs Discovery Reach at the Tevatron and the LHC



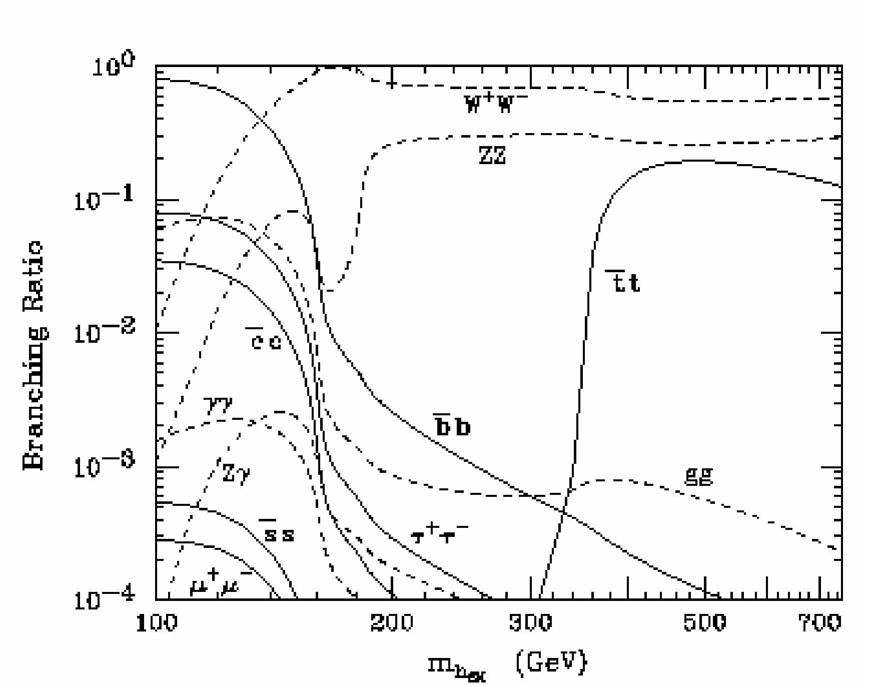


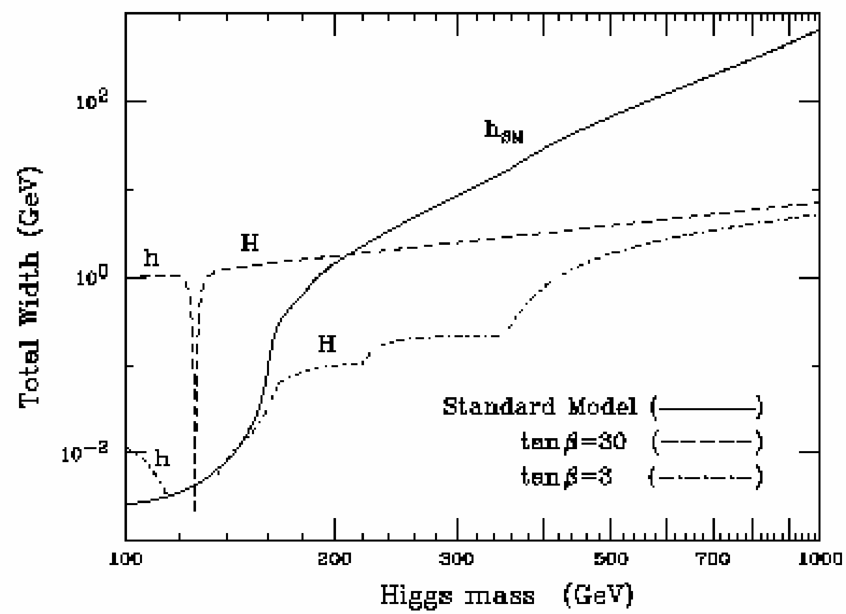
Tevatron can search for Higgs boson with mass up to about 200 GeV

This is the preferred range from precision data !

Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

SM Higgs Branching Ratios and Width





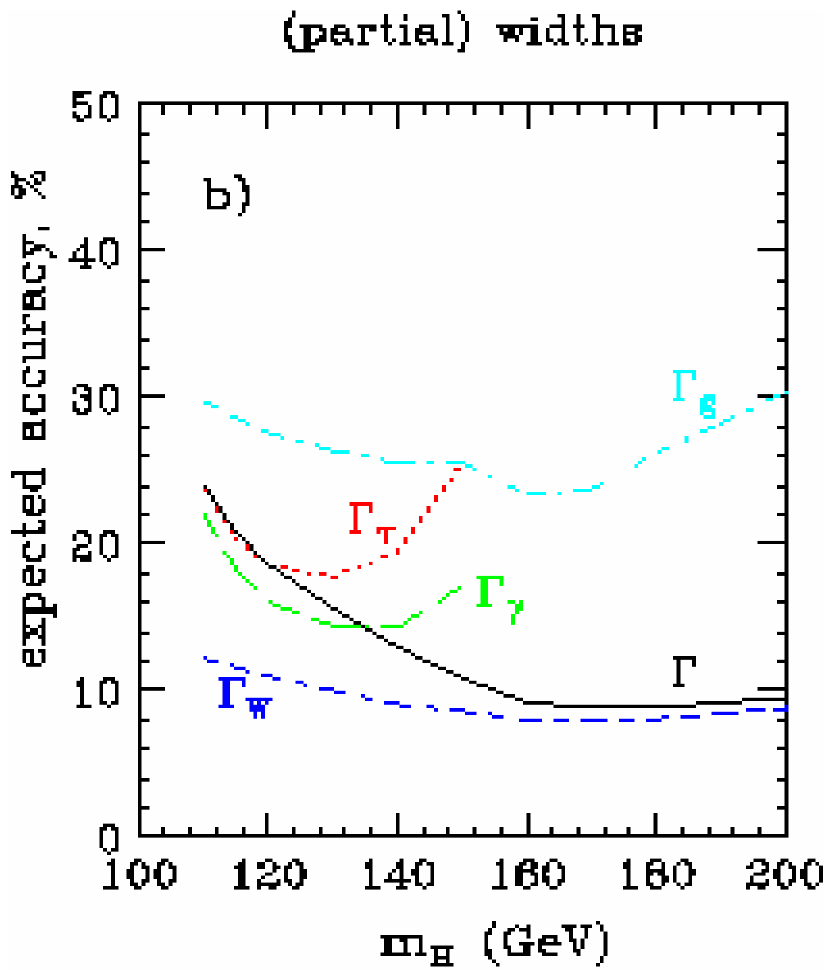
- Measuring Higgs couplings to bosons and fermions comes from meas. $\sigma(XX \to H_{SM}) \times BR(H_{SM} \to YY) \Rightarrow$ which implies measuring partial and total widths.
- **Measuring Higgs couplings to W and Z of order one (SM-like) will be evidence of a Higgs responsible for the EWSB mechanism**

A program of precision measurements will start at the LHC and will reach maturity at the LC

At the LHC

Many production and decay processes accesible

→ Combining meas. of partial ratios plus model dependent assumptions → Total Width



Absolute normalization of the Higgs WW coupling from Γ_W in weak boson fusion with $\phi \to WW^{(*)}$

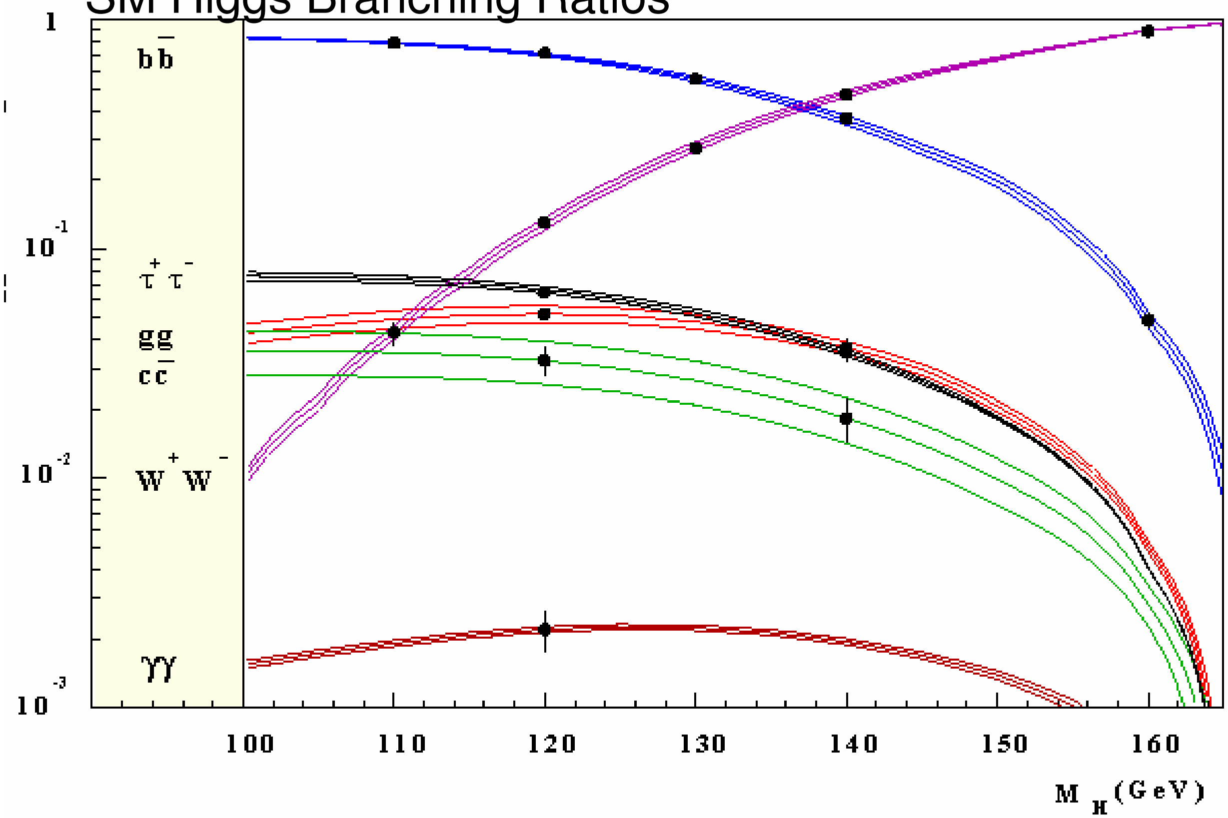
WW fusion is the most relevant channel to test EWSB mechanism

At the LC

Production mainly through:

$$e^+e^- \xrightarrow{Z^*} ZH_{SM}\,;\quad e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}H_{SM}\,;\quad e^+e^- \to t\bar{t}H_{SM}$$

SM Higgs Branching Ratios



Extraction of most BR's with 3-10% accuracy

Extraction of most couplings with 2-4% accuracy

HZZ coupling meas. via σ_{ZH} independent of Higgs decay modes!!

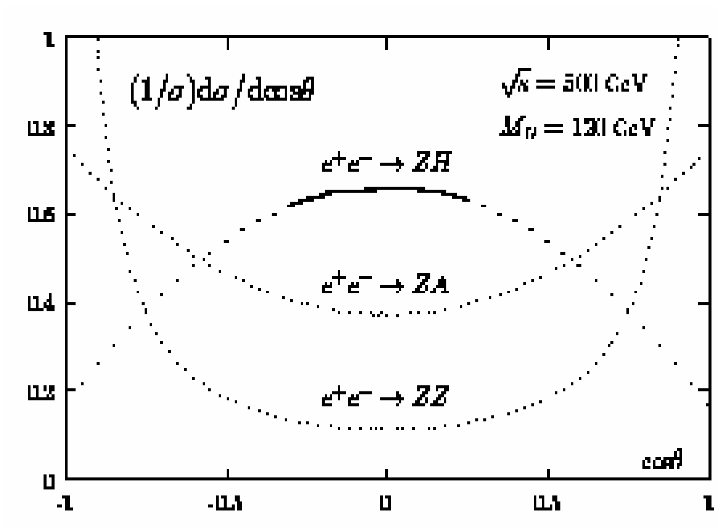
$$\delta\Gamma/\Gamma \approx 6\%$$

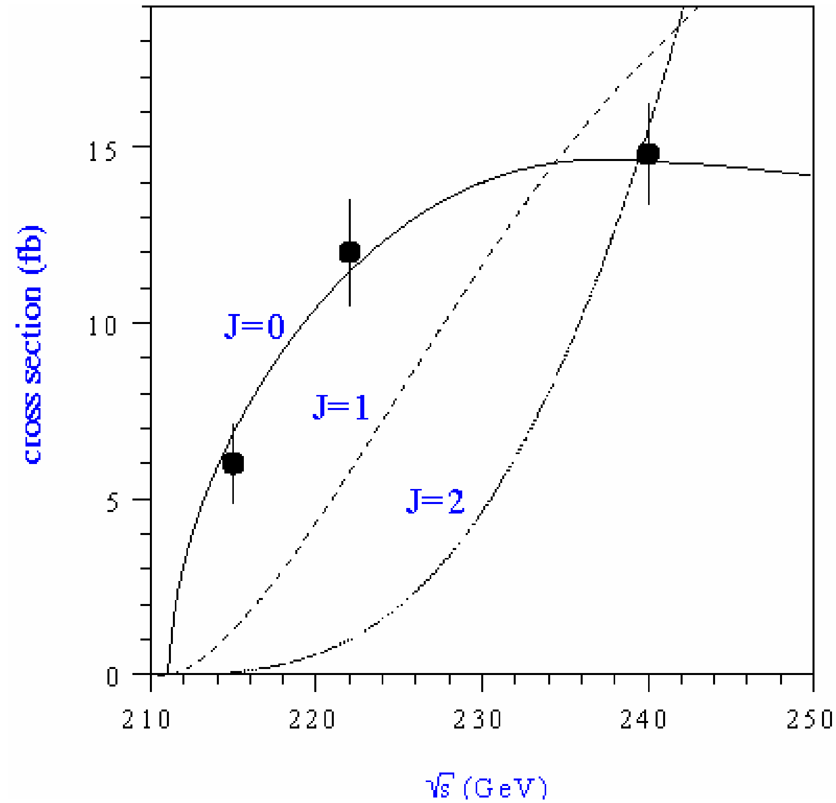
Higgs Decay Width: $\Gamma_{tot} = \Gamma_W / BR(H_{SM} \to WW)$ for mass of 120 GeV

Other Important Higgs Properties to measure

- **<u>Spin and Parity:</u>**

from threshold dependence of the excitation curve and angular distributions





- **Higgs Self Couplings**

Invisible Higgs Decays

- **CP nature of the Higgs Boson**

Neutral MSSM Higgs Searches

Main Production channels at hadron colliders

- **At the Tevatron**:

$$q\bar{q} \to Vh/VH \to Vb\bar{b} \text{ with V = W, Z}$$

$$p\bar{p} \to \phi b\bar{b} \to b\bar{b}b\bar{b} \text{ with } \phi = \text{A/h or A/H}$$

- **At the LHC:**

$$qq \to qqV^*V^* \to qqh, qqH \text{ with } h, H \to VV, \tau^+\tau^-, \gamma\gamma$$

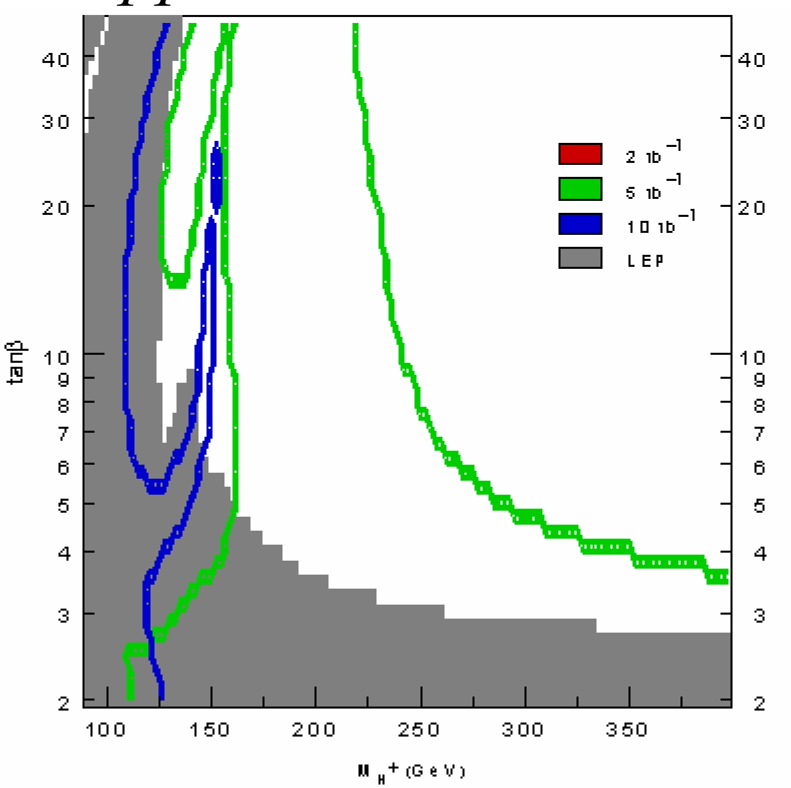
$$gg \to \phi \to \gamma\gamma; \qquad gg, q\bar{q} \to \phi t\bar{t} \text{ with } \phi \to \text{b}\bar{\text{b}}, \gamma\gamma, VV^*$$

- To explore reach of each collider, one defines benchmark scenarios without any assumptions of SUSY breaking mechanism. Fix set of SUSY particle masses, vary CP-odd Higgs mass m_A and $\tan\beta$

Discovery reach at the Tevatron and LHC

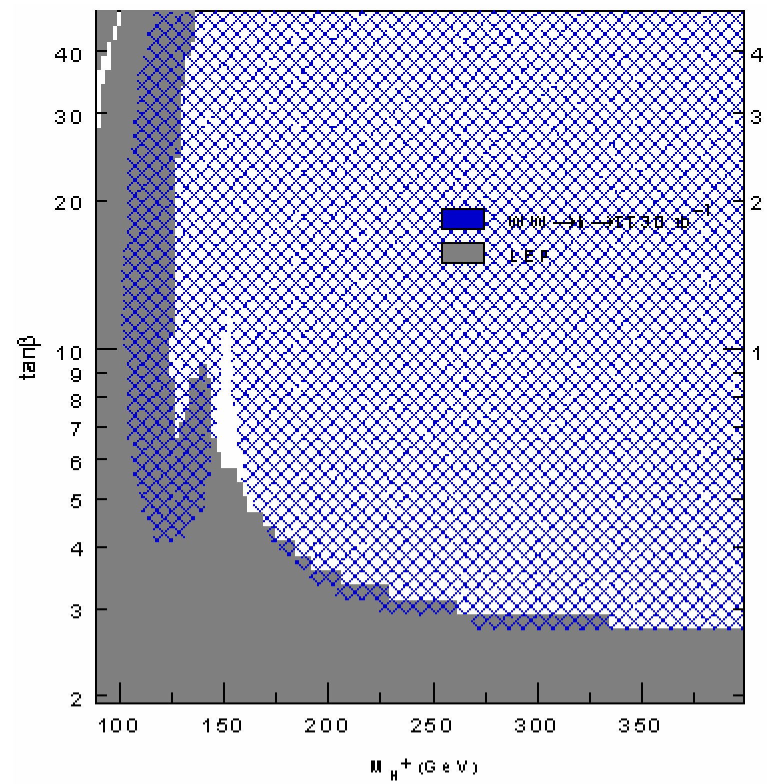
- SM-like Higgs Boson Reach

$$q\bar{q} \rightarrow Vh/VH \rightarrow Vb\bar{b}$$



At the Tevatron
95% C.L. limit

$$WW \rightarrow h/H \rightarrow \tau^+\tau^-$$



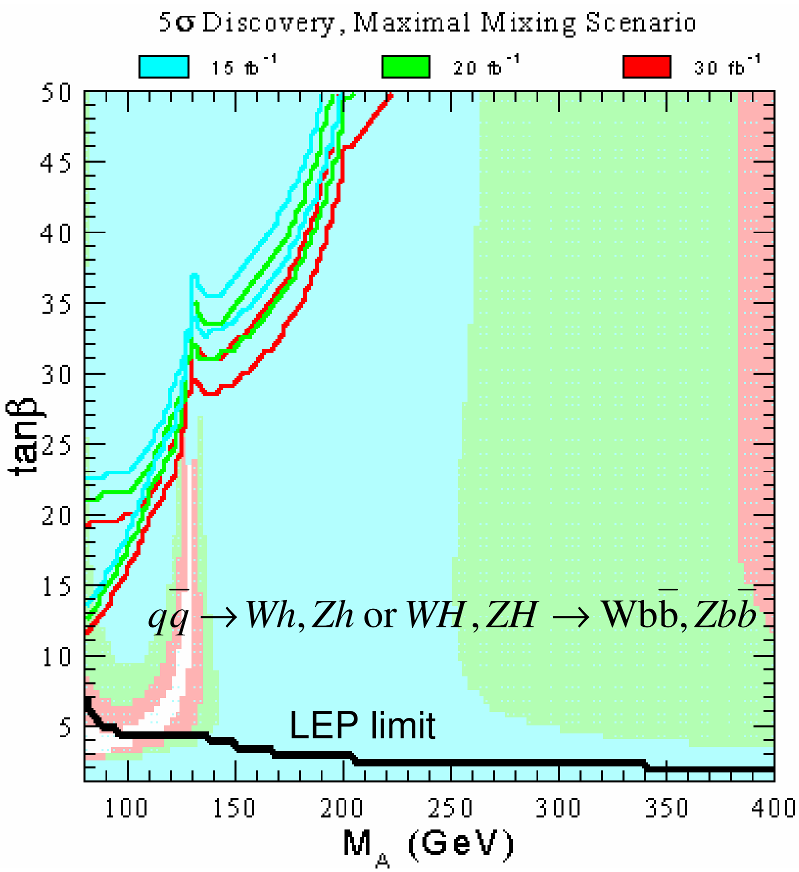
Similar coverage with tth-> ttbb channel and 100 fb-1

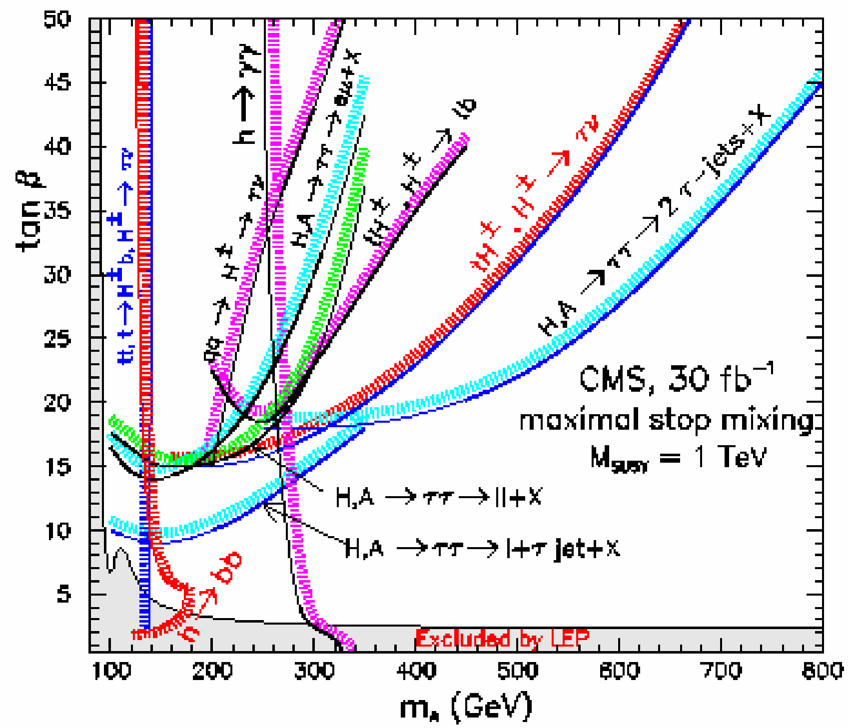
At the LHC

Discovery reach at the Tevatron and LHC

Many different channels at

the Tevatron and the LHC



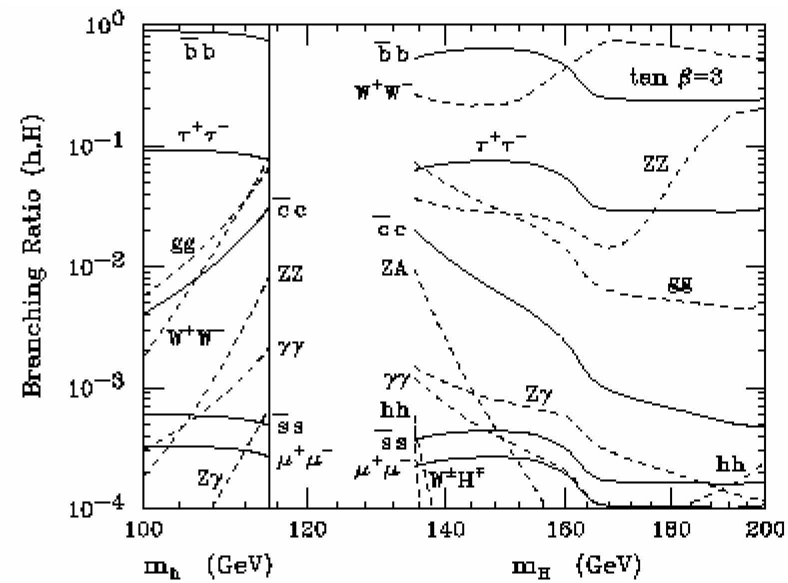


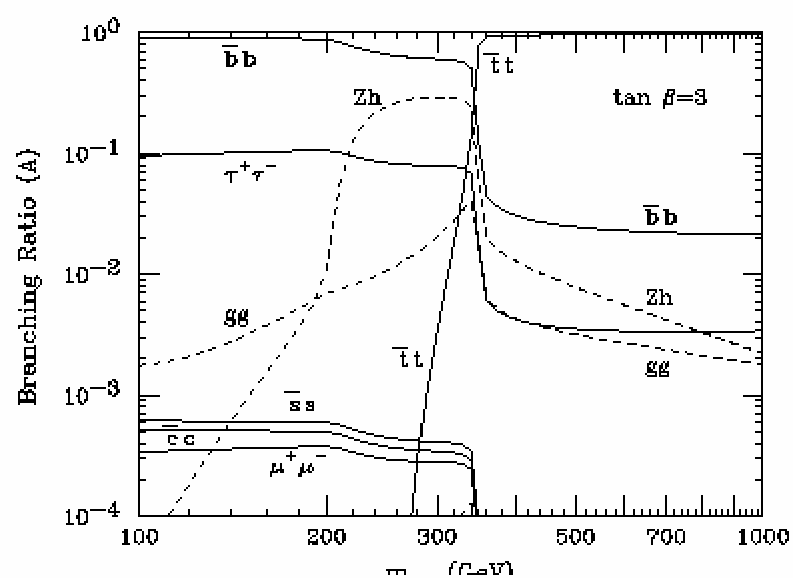
$gg, q\bar{q} \to b\bar{b}A, b\bar{b}h, b\bar{b}H \to b\bar{b}b\bar{b}$

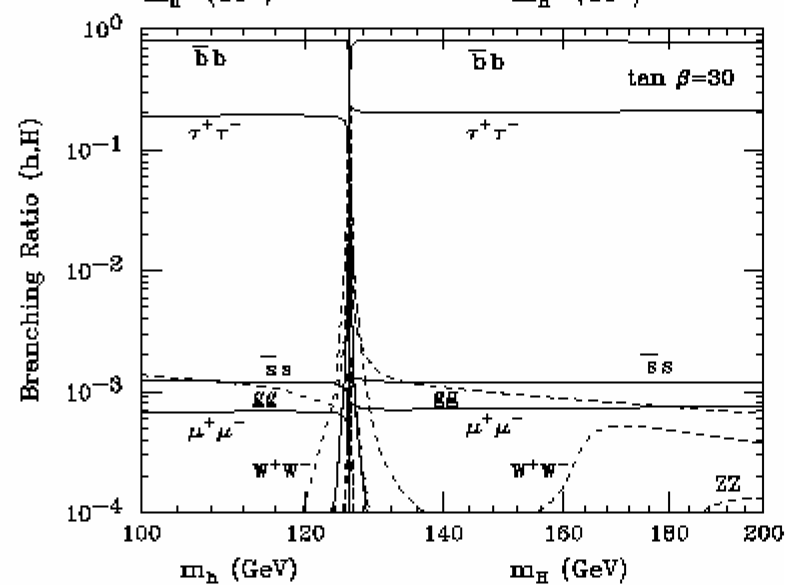
(upper-left region bounded by solid lines)

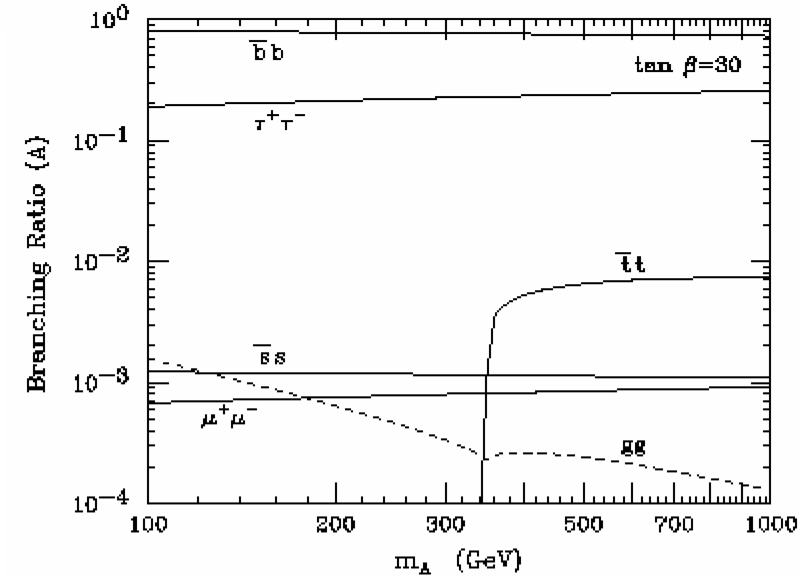
Neutral MSSM Higgs Branching Ratios

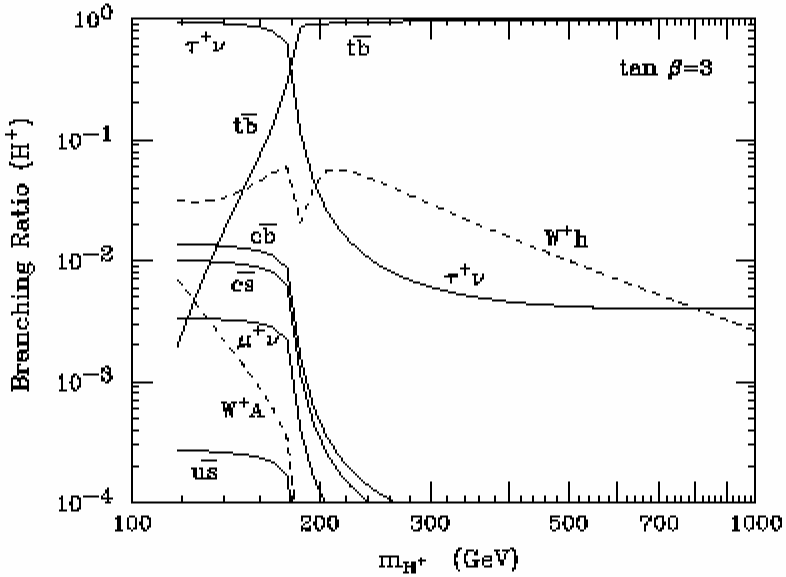
large $\tan\beta$: h, H, A to $b\bar{b}, \tau^+\tau^-$ dominate   low $\tan\beta$: richer pattern



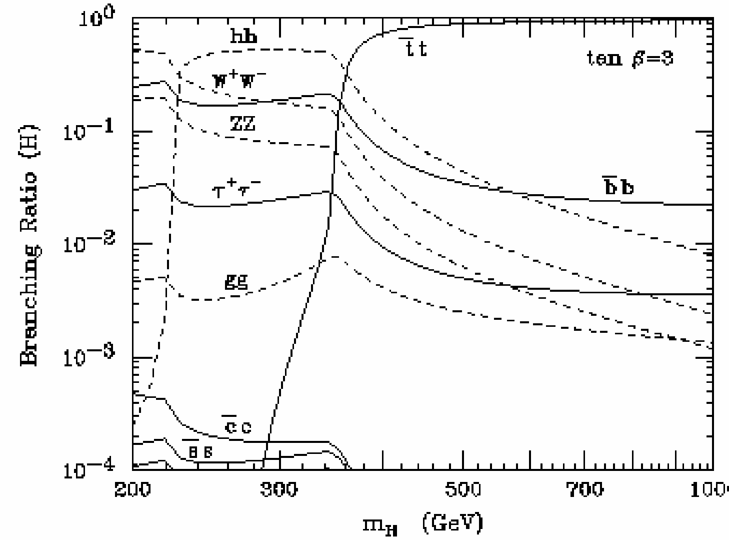




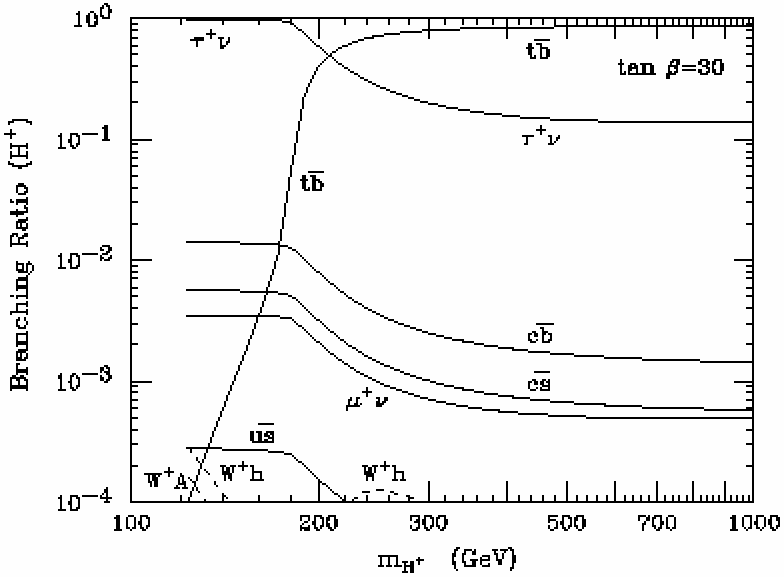




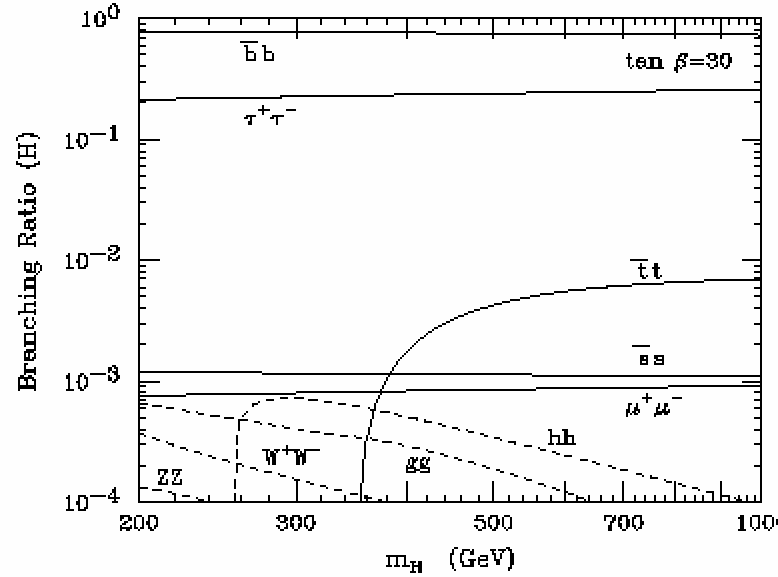
tan β=3
Branching Ratio (H+)
m_H+ (GeV)
τ+ν
tb̄
tb̄
W+h
cb̄
cs̄
μ+ν
W+A
us̄



tan β=3
Branching Ratio (H)
m_H (GeV)
hh
t̄t
W+W−
ZZ
b̄b
τ+τ−
gg
c̄c
s̄s



tan β=30
Branching Ratio (H+)
m_H+ (GeV)
τ+ν
tb̄
τ+ν
tb̄
cb̄
cs̄
μ+ν
us̄
W+A
W+h
W+h



tan β=30
Branching Ratio (H)
m_H (GeV)
b̄b
τ+τ−
t̄t
s̄s
μ+μ−
hh
W+W−
gg
ZZ

Precise measurement of widths and BR's

- Study departure of those quantities from SM predictions

Comparing widths and BR's of the SM-like Higgs boson of the MSSM and the SM Higgs of the same mass

$\Longrightarrow$ evaluate sensitivity to various observables

$$\delta\Gamma = |\,\Gamma_{MSSM} - \Gamma_{SM}\,| / \Gamma_{SM} \qquad \delta \mathrm{BR} = |\,\mathrm{BR}_{MSSM} - \mathrm{BR}_{SM}\,| / \mathrm{BR}_{SM}$$

demonstrate which quantities are most sensible to the non-standard nature of the Higgs boson

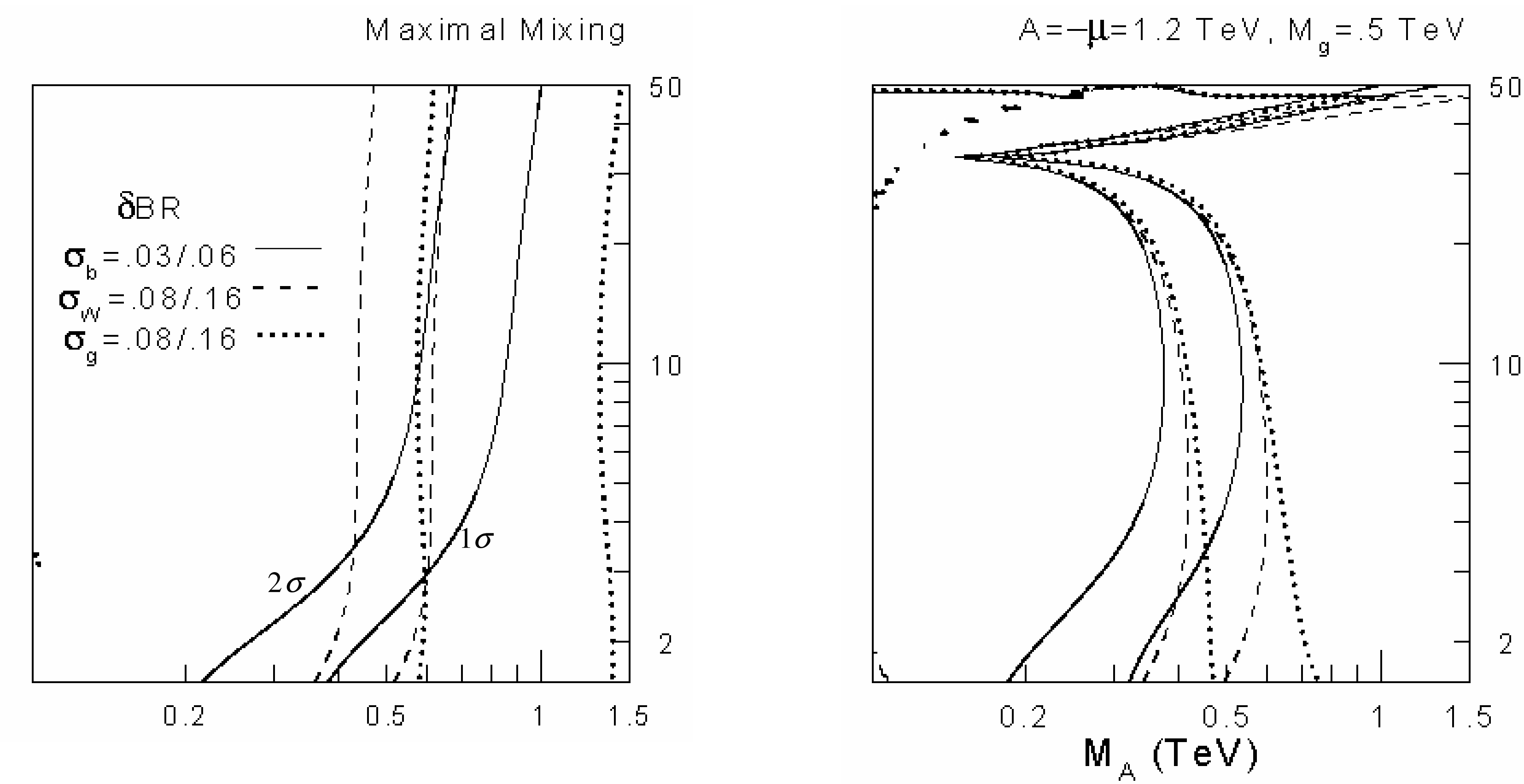
- in general, big deviations, except in decoupling limit, but this depends strongly on radiative correc., hence on SUSY parameters

at a LC: $e^+e^- \xrightarrow{Z^*} Zh\,,\, ZH\,,\, hA\,,\, HA\,; \qquad e^+e^- \to \nu\bar{\nu}h, \nu\bar{\nu}H$

- Distinguish MSSM from SM Higgs boson
- Provide Indirect evidence of a CP-odd mass beyond LHC/LC reach
- Provide information on SUSY vertex corrections to bottom Yukawa coupling

Precision Measurement of Higgs BR's at a LC

- The size of the deviation measures departure from SM limit (decoupling). If no deviation seen, one can deduce a bound on the heavy Higgs masses, which depends on the choice of SUSY param.



Conclusions

- **The SM is not yet complete: the nature of the Electroweak Symmetry Breaking dynamics is still unresolved**

Theoretical arguments suggest that the SM must be superseded by a more fundamental theory at the TeV-scale:

SUPERSYMMETRY is a leading candidate

The observation of a Higgs particle tests the EWSB mechanism

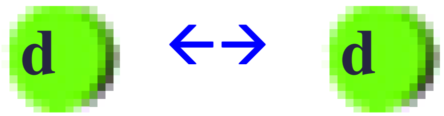
- **The Tevatron will have the first opportunity for discovery; success will require some improvement in machine performance, detector analysis and a little bit of luck**
- **The LHC will test it in many different ways and provide some useful precision measurements**
- **Precision tests will only be truly available at a future e^+e^- Linear Collider**

Nature may still have some surprises up her sleeve

We need to test the SM to higher energies and answer questions beyond it: Gravity, dark matter, baryogenesis, unification of forces

Expect theorists to keep busy speculating until data from future colliders provides some further guidance to nature's secrets at the TeV-scale

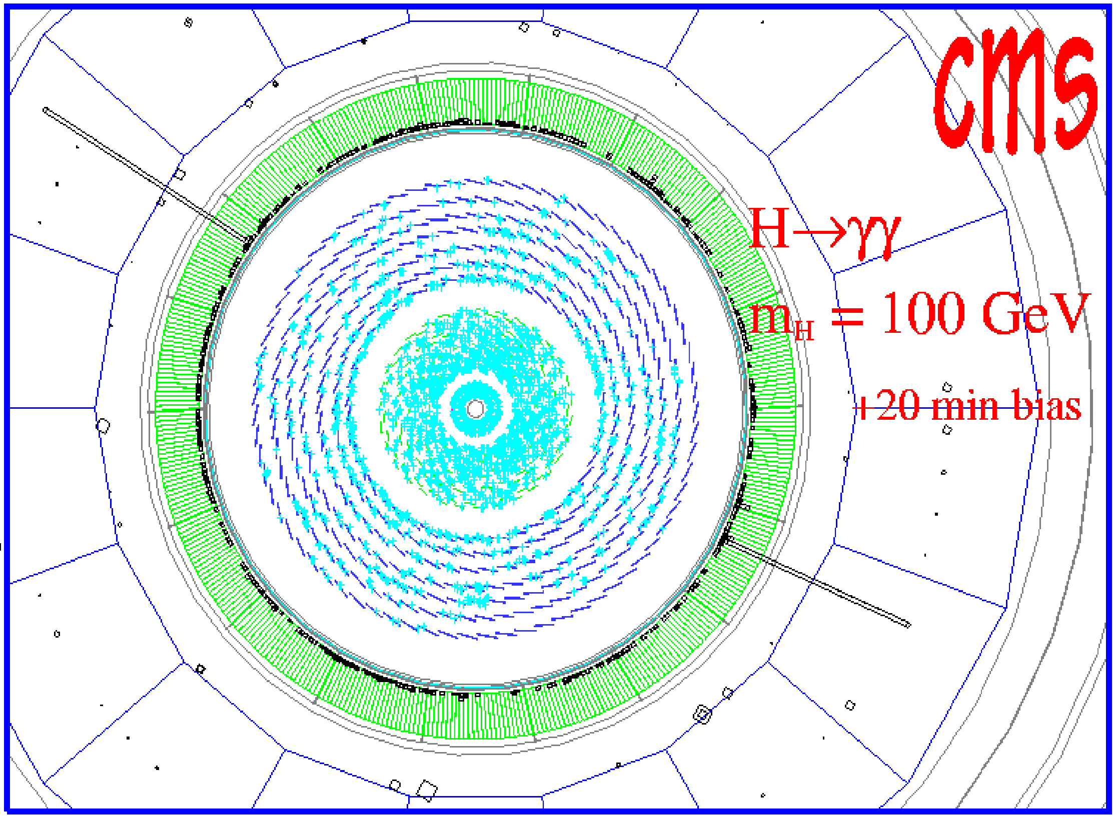
How strong is strong?



Relative Strengths and Ranges of Forces

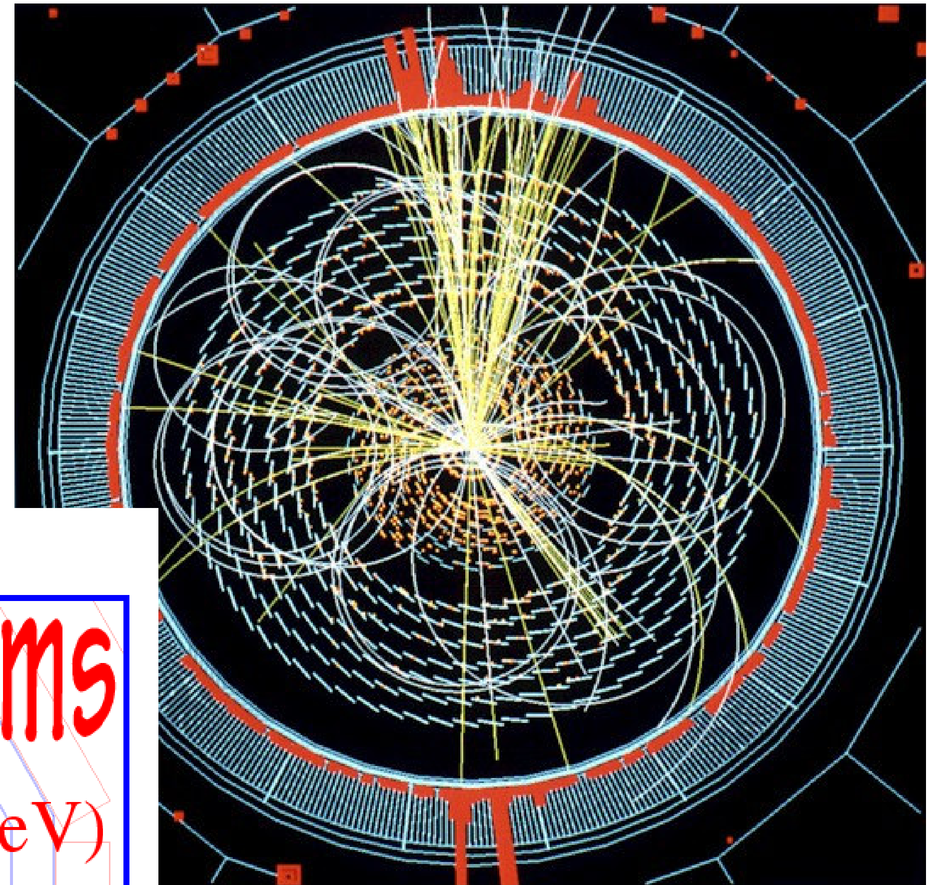
FORCE	RELATIVE STRENGTH	RANGE (m)
Strong	1	10^{-15}
Electromagnetic	1/137	infinite
Weak	10^{-5}	10^{-17}
Gravity	10^{-39}	infinite

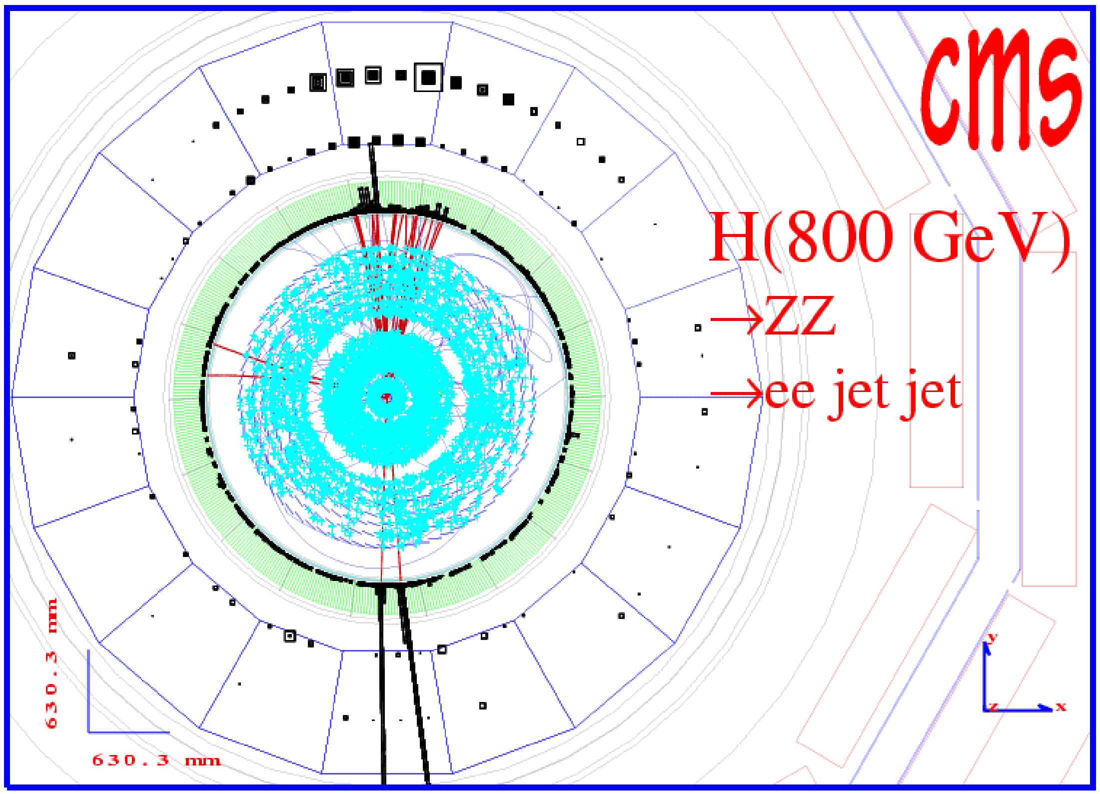
At LHC: **many different possibilities to look for a Standard Model Higgs boson with mass up** $m_{\phi} = 1000\, GeV$



How will a Higgs with mass lighter than 140 GeV look at LHC

How will a Higgs as heavy as 800 GeV look at the LHC





SM Higgs Poduction at hadron Colliders

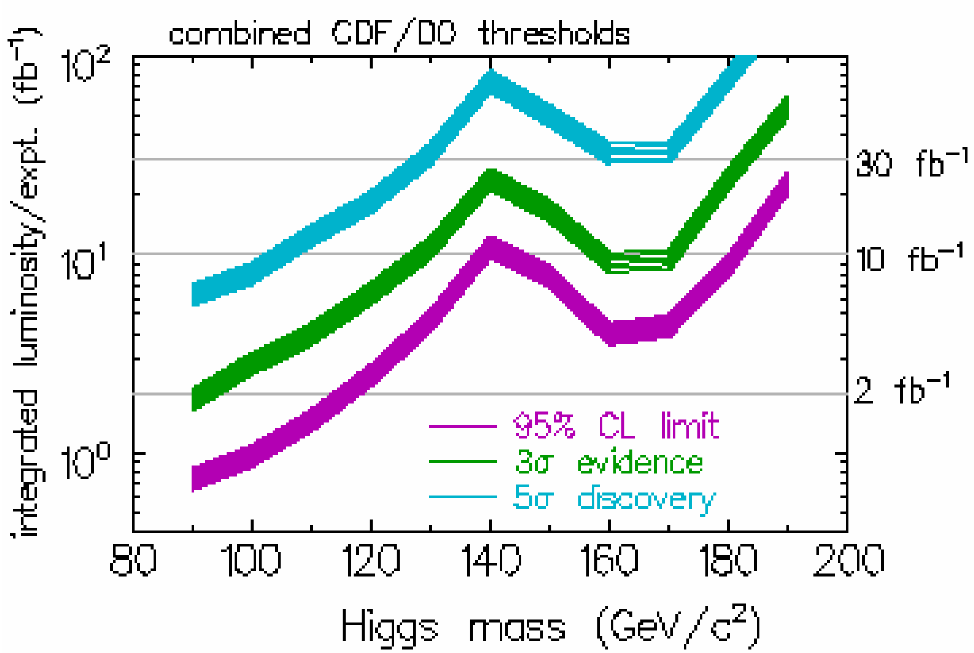
$$gg \to H_{SM} \to \gamma\gamma,\quad gg \to H_{SM} \to VV^{(*)} \quad with \quad V = W, Z$$

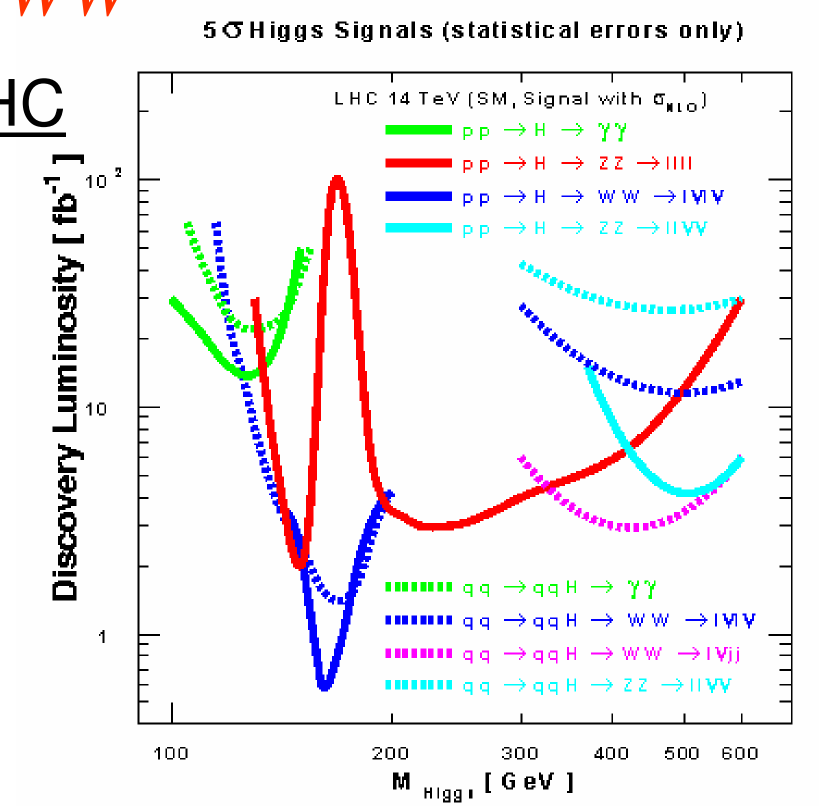
$$qq \to V^{(*)}V^{(*)} \to qqH_{SM},\quad H_{SM} \to \gamma\gamma, \tau^+\tau^-, V\,V^{(*)}$$

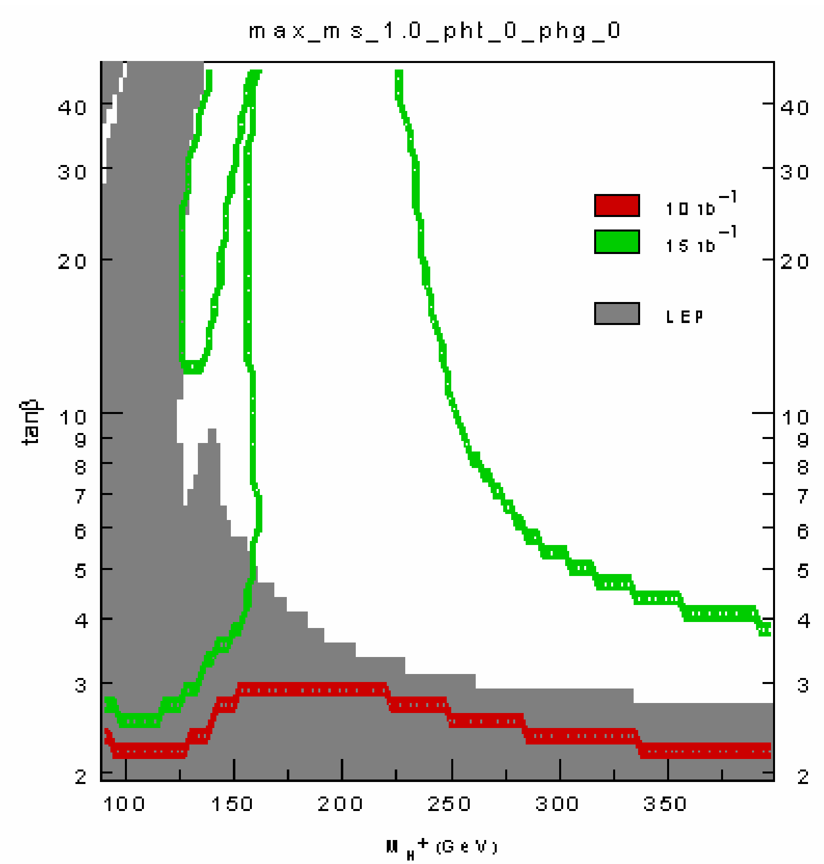
$$q\bar{q}^{(')} \to V^{(*)} \to VH_{SM},\quad H_{SM} \to b\bar{b}, WW^{(*)}$$

$$gg, q\bar{q} \to t\bar{t}H_{SM},\quad H_{SM} \to b\bar{b}, \gamma\gamma, WW^{(*)}$$

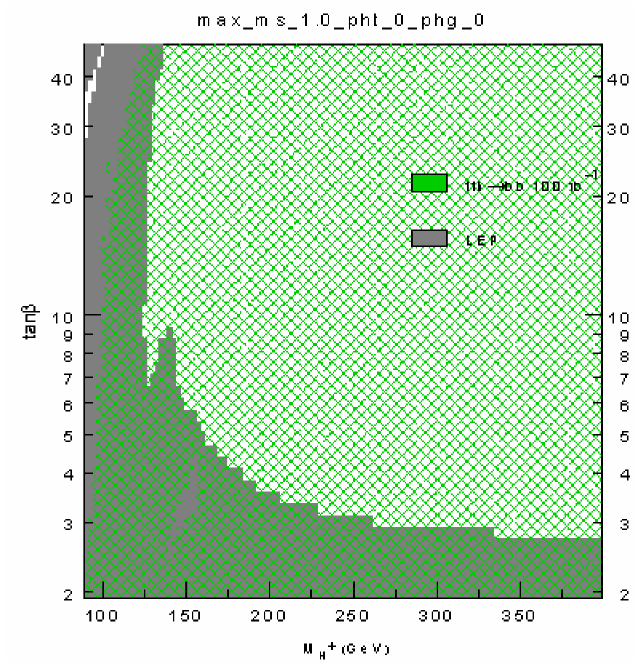
Discovery reach at Tevatron and LHC



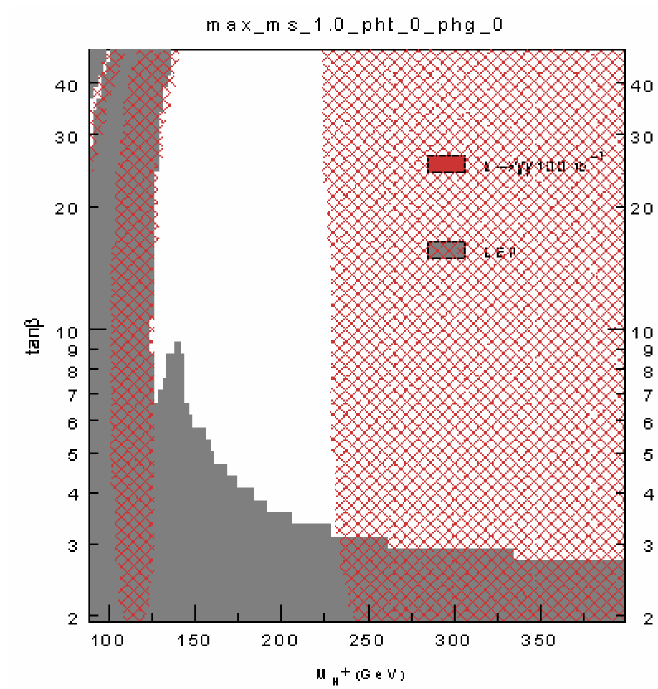




At the Tevatron: 5 sigma discovery



At the LHC



The Standard Model

A Quantum Theory that successfully describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

based on a gauge field theory with a symmetry group

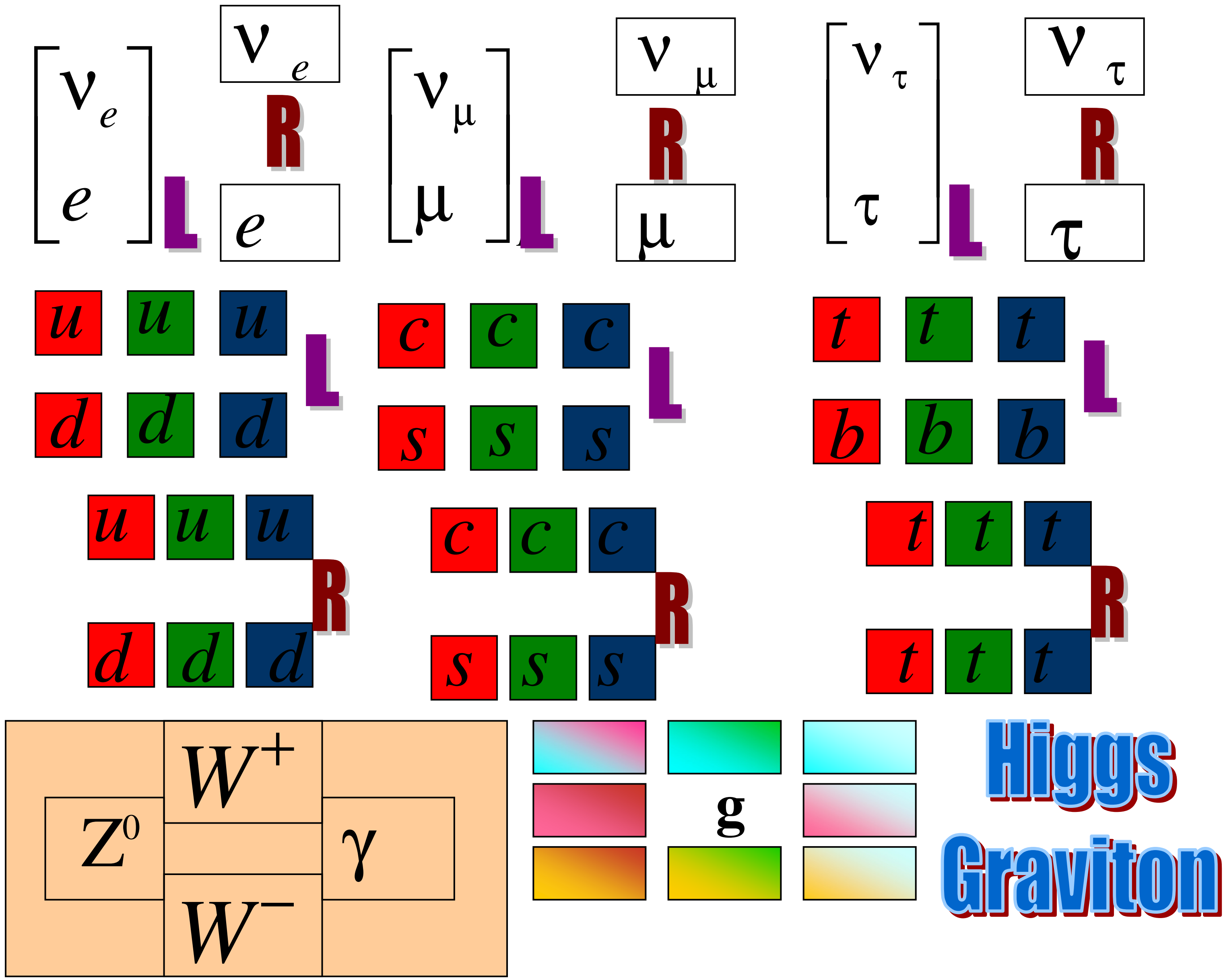
$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

There are 12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ and 3 gauge couplings: g_1, g_2, g_3

The matter fields :

3 families of quarks and leptons with the same quantum numbers under the gauge groups



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b b b
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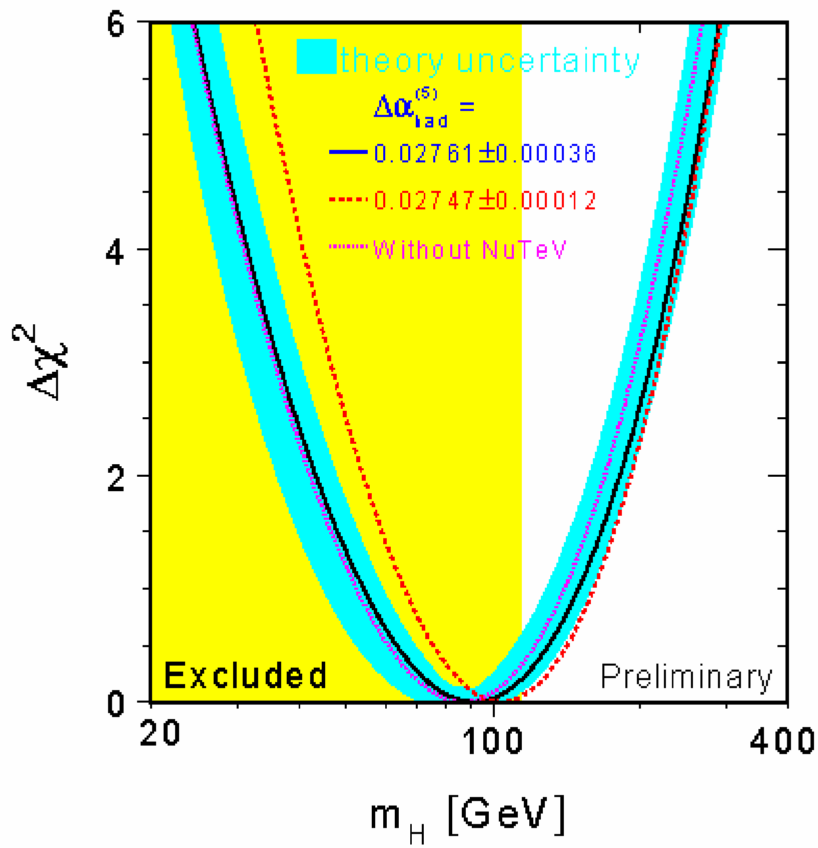
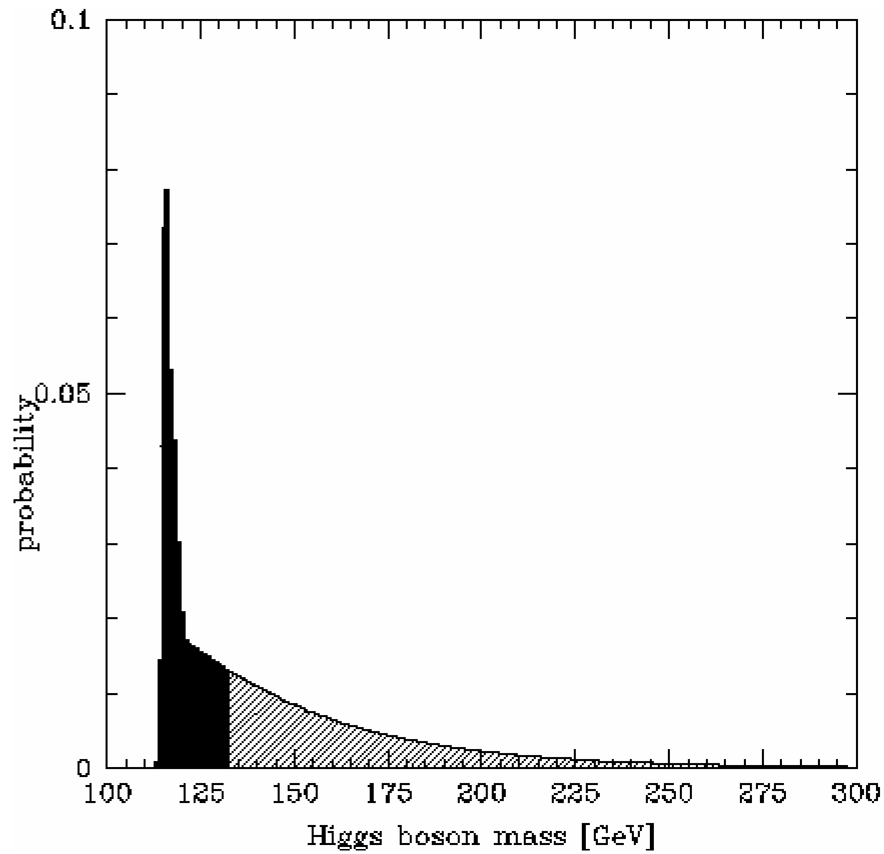
u u u
d d d
R
c c c
s s s
R
t t t
t t t
R
W+
Z0
γ
W−
g
Higgs
Graviton

Constraints on m_ϕ from precision electroweak data





$$m_\phi = 78^{+48}_{-31}\ GeV$$

$m_\phi < 193\ GeV$ at 95% C.L.

Within the SM → the Higgs is expected to be lighter than about 200 GeV

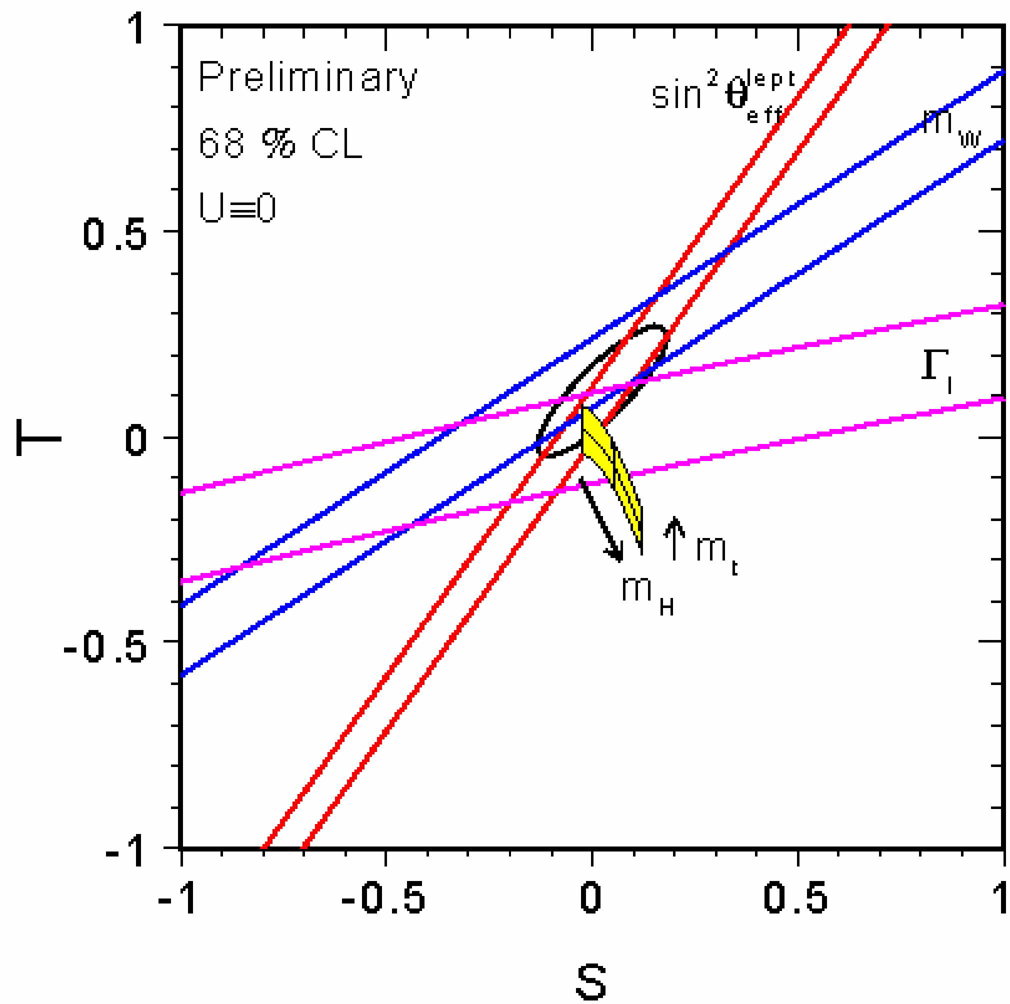
- If New Physics beyond the SM exists, most certainly will couple to SM particles and give contributions to SM observables via quantum corrections

- It has been shown that to avoid a light Higgs boson, the new Physics beyond the SM must be accompanied by new phenomena at scales below 1 TeV

It can be detected at present and future colliders

1. through direct detection
2. by improved meas. which detect deviations from SM

All present data is suggestive of a weakly-coupled Higgs sector



One can parametrize data in terms of effective S,T U parameters

Measured S, T, U parameter impose strong constraints on new physics, hence on alternative approaches to EWSB dynamics

<u>Strongly-coupled EWSB dynamics</u>

1. technicolor models
2. condensation models
3. little Higgs Models

possible, but not obvious that all phenomenological issues can be simultaneously solved

Low energy Supersymmetry

lesson from history: electron self energy → fluctuations of em fields generate a quadratic divergence but existence of electron antiparticle cancells it, otherwise QED will break down well below M_{Pl}

Will history repeat itself? Take SM and double particle spectrum

New Symmetry → SUPERSYMMETRY (SUSY)

For every fermion there is a boson of equal mass and couplings

Self energy of an elementary scalar related by SUSY to the self energy of a fermion → only log dependence on fundamental high energy scale!

SUSY must be broken in nature: no SUSY partner of SM particle seen

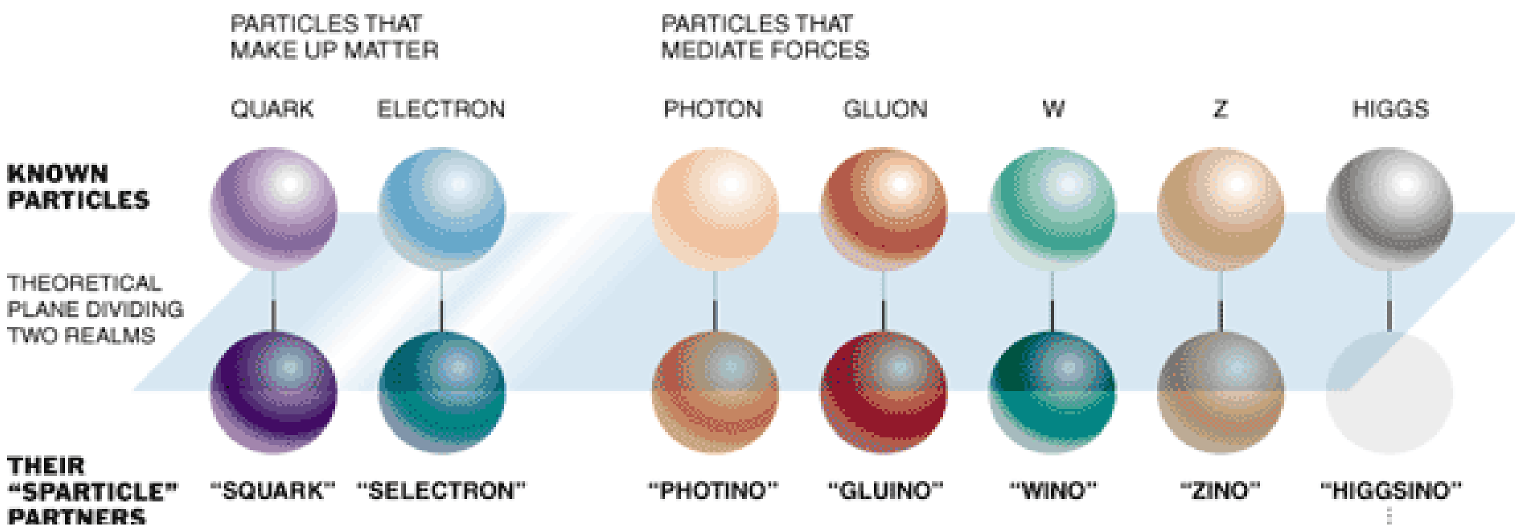
The scale of SUSY breakdown must be of order 1 TeV, if SUSY is associated with scale of electroweak symmetry breakdown

$$\Delta m^2 \approx g^2_{hf\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff} / m_h^2)$$

- **The origin of SUSY breakdown still not understood: TeV SUSY regime can give a glimpse of Planck scale physics**

supersymmetry

fermions ⟷ **bosons**



- none of the sparticles have been discovered yet
- it demands at least 4 different Higgs particles

Higgs Physics ⟶ Powerful test of SUSY